INVESTIGATIONS LEADING TO THE DEVELOPMENT OF THE OPTIMUM METHOD(S) FOR CHARGING SEALED NICKEL-CADMIUM BATTERIES

Report No. 1

Signal Corps Contract No. DA 36-039-SC-90823

DA Project No. 3A99-09-002

First Quarterly Progress Report
1 October 1962 to 31 December 1962

U.S. Army Electronics Research and Development Laboratory
Fort Monmouth, New Jersey

INLAND TESTING LABORATORIES
Cook Technological Center Division
COOK ELECTRIC COMPANY
Dayton, Ohio

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dated 20 September 1961

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This project is directed toward the development of an optimum method or methods for charging sealed Nickel-Cadmium batteries in a manner such that the method(s) developed are capable of being incorporated into a practical field charger.

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I. PURPOSE

The purpose of this study is to conduct investigations into various methods of charging sealed nickel-cadmium batteries which will result in the development of an optimum method or methods for charging sealed nickel-cadmium batteries at various ambient and initial battery conditions. It is intended that the optimum method(s) determined be capable of incorporation into a practical field charger.

The work effort of this program is divided into four phases of study, namely, investigations of charging procedures using constant current, constant voltage, two-rate constant current, and pulse charging. The investigations are being performed on two sizes of sealed nickel-cadmium cells (Type BB 412 ( )/U and BB 440 ( )/U). Test parameters presently established for consideration in the studies for the constant current charging method are:

1. Four ambient cell temperatures: -40°F, -10°F, 75°F and 125°F.
2. Four Charge Periods: 1, 4, 8 and 16 hours.
3. Three States of Charge (0, 33, 66%).
4. Two levels of Overcharge (Pre-selected according to conditions).
5. Two Discharge Rates (5-hour and 15-minute).

II. ABSTRACT

Experiment designs, test data, analyses and results for investigation of constant current charging at 75°F, 125°F, -10°F and -40°F for fully discharged cells are presented.

Tests at the two higher temperatures included test variables of ambient cell temperature, charge period, percent overcharge, cell size and discharge rate. Tests at the two lower temperatures involved all of the foregoing test variables except cell usage was substituted for charge period. Cells of Type BB 412( )/U and BB 440( )/U were used in these investigations.

Analysis of the charging procedures is based upon the percent of capacity obtained at test conditions to that obtained at standard conditions. Since only the constant current charge method has been investigated thus far, no conclusions can be drawn pertaining to the optimum charge method. However, analysis of the constant current data shows that ambient temperature, discharge rate, cell type and the interaction between cell type and discharge rate are the main factors controlling the capacity obtained over the selected levels of the test variables. Charge time and percent overcharge do not show up as significant factors over the selected levels.

III. CONFERENCES AND PUBLICATIONS

Three conferences were held during this first quarterly report period.

The first conference was held at Fort Monmouth, New Jersey on 3 October 1962 and consisted of two parts. The first portion of the conference was devoted to review and definition of technical detail requirements for the program. Present at this meeting were Me'srs. P. Rappaport, B. Resnic of the U.S. Army Electronic Research and Development Laboratory and Messrs. W. Ingling, I. Luke of Inland Testing Laboratories. The application and use of statistical experiments and techniques for this program were discussed in the second part of this conference. In attendance were those representatives present at the first part of the conference, Mr. Cuthbert Daniel, Consultant to the USAELRDL, and additional key personnel of the U.S. Army Electronics Research and Development Laboratory.

The second conference was held at Ft. Monmouth, New Jersey on 24 October 1962 for review and preliminary analysis of test data from the initial experiment. In attendance at this conference were Mr. Cuthbert Daniel, Consultant to the USAELRDL, Messrs. P. Rappaport and B. Resnic and other key members of the U.S. Army Electronics Research and Development Laboratory and Messrs. W. Ingling, I. Luke, and R. Koesters of Inland Testing Laboratories.

The third conference was held at Inland Testing Laboratories, Dayton, Ohio on 12 December 1962 for discussion and review of the experimental data analyses and subsequent experiment designs. Present at this conference were Mr. B. Resnic of the U.S. Army Electronics Research and Development Laboratory and I. Luke, R. Koesters and other key personnel of Inland Testing Laboratories.

Publication and reports for reference in the program were:

1. Daniel, Cuthbert, "Use of Half-Normal Plots in Interpreting Factorial Two Level Experiments" Technometrics, Volume 1, Number 4, November 1959.

2. Wilburn, N. T., "Application of 2^{8-4} Fractional Factorials in Screening Variables Affecting the Performance of Dry Process Zinc Battery Electrodes", Presented at Eighth Conference on Design of Experiments in Army Research, Development and Testing, October 1962.

3. Alliegro, F. and Mundel, A. B., "High Capacity Sealed Nickel-Cadmium Batteries", Proceedings 15th Annual Power Sources Conference, May 1961.

4. Clark, W. W. and others, "Alkaline Battery Evaluation", Technical Documentary Report No. ASD-TDR-62-893, Inland Testing Laboratories, October 1962.

5. Dittmann, J. F., "Effects of Ambient Temperature on Performance Characteristics of Nickel-Cadmium Battery, BB-422/U, Final Report, Eagle-Picher Company, March 1962.

6. Davies, O. L. and others, "Design and Analysis of Industrial Experiments" 2nd ed., Hafner Publishing Company, 1960.

7. Cox, D. R., "Planning of Experiments" 1st ed., John Wiley and Sons, Inc., 1958.

8. Kempthorne, O., "The Design and Analysis of Experiments" 1st ed., John Wiley and Sons, Inc., 1952.

The assistance and information contributed to this program by Mr. Cuthbert Daniel, consultant to the USAELRDL, and Mr. Paul Rappaport and Mr. Burton Resnic, USAELRDL technical representatives, is gratefully acknowledged.

IV. FACTUAL DATA

A. Introduction

An optimum charging method indicates that method which will produce an ampere-hour input to return the battery to a state-of-charge (following a discharge), so that the maximum capacity may be obtained on a subsequent discharge without causing degradation or reducing the cycle-life expectancy of the battery.

An adequate charging procedure could be readily defined for fully discharged batteries at room temperature conditions and when sufficient time for recharge is available. However, in field and service use applications, stabilization of the battery at the most favorable charging conditions may not be feasible or the time for the best charging period may not be available. Therefore, it is necessary to develop or define the optimum procedure(s) for charging batteries at the conditions encountered in these field applications.

In determining optimum charging procedures for sealed nickel-cadmium batteries under various conditions, consideration must be given to the large number of variables which affect the charge-discharge characteristics, charge efficiency, and cycle-life performance of the cells. In order to give consideration to all possible significant variables and their ranges or levels as outlined in the Technical Requirements for this program, a large number of tests

and cells would be required to cover all combinations of the variables if only one factor (variable) was varied at a time. The use of statistical experiments was considered for determining the effects of the variables on the capacity and performance of the cells.

For a study of the variation caused by deliberate changes in the test conditions a generally useful technique is provided by the Factorial Experiment. A factorial experiment can be used to isolate the significant variables affecting the cell capacity output and to evaluate the dependence of the effect of a variable on the variation of the other variables. Because the required information can be obtained with the desired degree of precision and a minimum expenditure of effort, it was decided the use of factorial experiments was the most efficient and economical method for accomplishing these investigations. Also, since it would be impractical to include the combinations of those test conditions, where prior information shows that satisfactory charging cannot be accomplished or cell damage prevented, a series of small experiments were established rather than a complete factorial for all the investigations. This leaves the program free for testing additional variables at some test conditions or for investigating further those variables which initial analyses show to be most important.

The test conditions established for the constant current charging method are shown in TABLE I, below:

TABLE I. - Constant Current Test Conditions

Ambient Temp. (°F)		Charging Time (Hours) 1	4	8	16
+125	Overcharge (%)	110 130	120 140	120 155	140 170
	Initial State of Charge (%)	0	0	0 33 66	0 33 66
+75	Overcharge (%)	110 130	120 140	120 155	140 170
	Initial State of Charge (%)	0	0	0 33 66	0 33 66
-10	Overcharge (%)				140 170
	Initial State of Charge (%)				0
-40	Overcharge (%)				140 170
	Initial State of Charge (%)				0

Two cell sizes: 3.5 and 10 A.H.
Two Discharge Rates: 15-minute and 5-hour

This first quarterly report covers two experiments for constant current charging of fully discharged cells shown as 0% state of charge in the table above. The first experiment was designed for

the constant current charging investigations at 75°F and 125°F, for the 0% state of charge, and the second experiment involved the 16-hour charge tests at -10°F and -40°F. The charges performed in the experiments were evaluated on the basis of the capacity obtained at the test conditions compared to the capacity obtained for the cell on a normalizing cycle. The normalizing cycle consisted of charging at a constant current rate of 0.2C (C = rated capacity) for 8 hours and discharging at the five-hour rate (0.2C) to 1.0 volt/cell at 75°F.

Capacities at the experiment test conditions were determined at the 5-hour (0.2C) and the 15-minute (3C) discharge rates. Different ranges of overcharge (percent of rated capacity) were selected for each of the 1, 4, 8, and 16-hour charge periods to insure that the cells could become fully charged at the test temperatures and yet eliminate the possibility of considerable gas or heat generation caused by excessive overcharge.

B. <u>Description of Cells Used for Investigations</u>

Two sizes of sealed nickel cadmium cells were used for these tests of constant current charging procedures. The smaller cells were Type BB 412( )/U rated at 3.5 ampere-hours and designed to meet the requirements of MIL-B-55130 (Sig C) and MS Standard MS 75031 (Sig C). The larger cells were Type BB 440( )/U rated at

10 ampere-hours and designed to meet the requirements of Signal Corps Technical Requirement SCL-7504.

The 3.5 A-H cells were "D" size cells with a button-type positive terminal and the case for the negative terminal. These cells were designed with spirally-wound plates. The 10 A-H cells were cylindrical with a nominal outside diameter of 1.8 inches and a cylinder height of 6 inches. Overall height of the cells was a nominal 6.5 inches. The cells were designed with two sizes of flat, rectangular plates within the cylindrical case and were equiped with two-insulated stud-type terminals and a resealable vent at the top. The case material of these cells was stainless steel.

The cells were received in a discharged condition. Upon receipt, all cells were visually inspected for evidence of damage and electrolyte leakage, and then were given an initial charge-discharge cycle at room temperature prior to any program tests. Number labels were affixed to the cells for identification purposes throughout the tests. The cell cases were not mechanically restrained or attached to heat-conducting materials other than the electrical leads during the tests.

C. Constant Current Charging Method

1. Charging at 75°F and 125°F (Design I)

In establishing the design of the experiment for constant

current charging at 75°F and 125°F, it was decided to limit the variables to five. The variables selected are shown in Figure 1. High (+) and low (-) levels were assigned to each of the variables. Since four levels of charge period (1, 4, 8 and 16 hours) were to be investigated at 75°F and 125°F, factors B and C and their interaction (BC) were used to represent this four-level variable. Therefore, the factor B is always accompanied by the factor C and vice versa. As mentioned earlier in the Introduction, the degree of overcharge was given a defined high and low level for each charge period, to insure that the cells could be charged at the temperatures, and yet eliminate the possibility of cell damage from excessive overcharge. It is recognized and should be pointed out that, in general, the most important part of a factorial experiment is the establishment of the variables and their levels.

With the variables and their levels established, the 2^{6-1} factorial design was established as shown in Figure 2. The design has six factors each at two levels and incorporates thirty-two individual cells. A full 2^6 factorial experiment involves sixty-four trials, therefore, this design was a half-replicate. The design was based on the extension of a 2^5 factorial for a total of 32 trials. The remaining factor was intro-

duced by making the assumption that the three, four, and five-factor interactions between the first five factors are negligible. The factor F was, therefore, introduced by equating it to the almost certainly negligible interactions of the first five variables. The high level of the variables was considered positive (+) and the low level minus (-) and the sign or level of the factor F (discharge rate) was determined from the product of the signs (+ or -) of the first five variables. Thus, from Figure 2, F for the first trial is - x - x - x - x - = -, F for the second trial is + x -x - x - x - = +, etc.

The design of the experiment in terms of the test conditions for each run is shown in Figure 3. Each cell was equipped with a set of four leads with two leads attached to each terminal. The larger leads were used for charging and discharging currents while the smaller leads were used for remote sensing to the power supply and voltage recordings. Prior to the tests, each cell was subjected to a normalizing cycle consisting of an eight-hour charge at a C/5 rate at room temperature and discharged at a C/5 rate at room temperature and recording the elapsed time to a cell potential of 1.0 volt. To insure that the cells were at the same state of discharge, the discharge at C/5 rate at room temperature was continued to an end-potential

of 0.6 volts. The cell was stabilized at the test temperature prior to the test and the temperature of the cell under test was measured by means of a thermocouple attached to the negative terminal of the 10 A-H cells and to the can of the 3.5 A-H cells. The cells were then tested individually at the controlled conditions set forth in the experiment. An open circuit stand period of one hour was maintained between completion of the charge period and the start of the discharge. The cell terminal temperature, as measured with the termocouple, attained the ambient test temperature within one hour after the end of the charge period. Discharges and charges were performed at the same ambient test temperatures. The cells were discharged at the experimental test rate to a potential of 0.6 volt, recording the time for the cell to reach 1.0 volt.

The response in the experiment is the ratio, expressed as a percent, of the ampere-hours output during the Design I tests to the ampere-hours output during the normalizing cycle. The cell data for the Design I tests are shown in Figure 4 and the responses in percent for each run are listed in Figures 2 and 5.

The analysis of the thirty-two responses is shown in Figure 5. The arithmetic technique used, called Yates'

Algorithm, is a rapid method of obtaining the mean effects and interactions. Yates' Algorithm has its own check and thus eliminates mistakes which may occur in long calculations.

The mechanics of the Yates" Algorithm is as follows:

The first figure of Column (1) is obtained from the sum of responses 1 and 2. The second figure is the sum of 3 and 4, etc. The 17th figure of Column (1) is the Algebraic difference of responses 2 and 1 (sign of response 1 reversed). The 18th figure is the Algebraic difference of responses 4 and 3, etc. Column (2) is obtained from column (1) in the same manner Column (1) was obtained from the responses. Additional Columns are derived by the same operation up to K number of columns, where the number of observations is 2^K. In this design K = 5 since 32 (observations) equals 2^5. The arithmetic for each column is checked before proceeding to the next column. The sum of column (1) is equal to twice the sum of every second response. The sum of column (2) is equal to four times the sum of every fourth response. The sum of column (3) is equal to eight times the sum of every eighth response. The sum of column (4) is sixteen times the sum of the sixteenth and thirty-second response. The sum of column

(5) is thirty-two times the thirty-second response. The mean effects are obtained by dividing column (5) by one half the number of responses. The first figure of the mean effects column is twice the average of the responses and is not used in the remainder of the analysis.

The thirty-one mean effects were arranged in order of magnitude without regard to sign. This ordered series was then arranged in half normal plot as shown in Figure 6 to interpret the significance of each effect. The ordinate of the plot is the order series of the thirty-one effects from the smallest to the largest. The abscissa is the magnitude of the mean effects. An error best straight line was drawn through the lowest twenty-four points. The mean effects having a large magnitude and falling significantly off the line are judged to be controlling factors in this experiment.

The σ_y estimated from the line in Figure 6 is 4 X 2 2 = 11.5. It does not seem likely that σ for responses around 20 (two of the responses were 20.9 and 29.1) would be the same as for the responses around 100. Also, it can be assumed that the responses might have constant percentage error, that is, σ divided by Y might be constant and if so, the logarithms of the responses would have constant precision. Therefore,

an analysis using logarithms of the responses was performed and is shown in Figure 7.

Figure 8 is a half normal plot of the logarithms of the measured effects. It shows that five effects are off the error best straight line and these are judged significant. The lower twenty-six effects were again plotted on half normal paper to obtain a more precise error best straight line and is shown in Figure 9. The standard error derived from this plot, in logarithmic form is 0.078.

In order to check the validity of the experiment and the judgement that the five effects (F, A, EF, E and B) falling significantly off the line in the plot Figure 8 were the controlling factors in the experiment, a Reverse Yates' Algorithm was performed to obtain a series of thirty-two predicted responses with the lower twenty-six effects set to zero. These Reverse Yates' computations and the predicted logarithms of responses are shown in Figure 10. The difference between the logarithm of the observed responses in Design I and the predicted logarithms of responses are shown in Figure 11. These differences were plotted on residual paper as shown in Figure 12 to obtain a second standard error of 0.07. This agrees very favorably with the error derived from the half-

normal plot in Figure 9.

As shown in the analysis of this experiment ambient temperature (A) and discharge rate (F) were controlling factors in the capacity obtained from the cells. From Figure 5 the sign of the mean effect of A (temperature) is minus and the sign of the mean effect of F (discharge rate) is plus, indicating that higher efficiencies can be obtained at the temperature selected for the low level and the discharge rate selected for the high level (75°F and 5-hour, respectively, reference Figure 1). The average of the response of all cells tested at 75°F was 77.8% while the average response of the cells at 125°F was 58.5% compared to an average of 68.2% for all 32 responses. The average response for the cells at the long discharge time (5-hour rate) was 80.4% and the average response of the cells at the 15-minute rate was 56%.

Also, in the analysis of this experiment and from Figure 8, cell size in terms of discharge rate was a controlling factor. The average responses for the 3.5 A-H and 10 A-H cells at the five-hour rate were 82.1% and 78.7%, respectively, whereas the average responses for the 3.5 A-H and 10 A-H cells at the 15-minute rate were 45.6% and 66.3%, respectively. This indicates that better performance can be

expected from the 10 A-H cells at higher discharge currents and can be explained by the different designs of the cells.

The efficiency of the cells, on the average, decreased with increased charge time. The average responses for both cell sizes were 73.7% for the one-hour charges, 70.1% for the four-hour charges, 66.5% for the eight-hour charges and 62.3% for the sixteen-hour charges.

The overcharge (D) for the ranges (levels) selected was not a controlling factor in this experiment.

Charge and discharge voltage characteristics versus ampere-hours for the 32 test runs performed in Experiment I on fully-discharged cells are shown in Figures 13 through 20. All charges and applicable discharges for a single charge time (1, 4, 8 or 16 hrs.) and one temperature (75°F or 125°F) are plotted on a single sheet. Therefore, each graphical Figure presents a charge characteristic for the high and low level of overcharge and a discharge characteristic for the 5-hour and 15-minute rate for each cell size.

Charge and discharge voltage characteristics for a typical normalizing cycle are shown in Figure 21.

Variables	Factor	Level of Factor	
		High	Low
Temperature	A	125°F	75°F
Charge Period	B	8 hr. *	16 hr. *
	C	1 hr. *	4 hr. *
Overcharge	D	130% (1 hr.)	110% (1 hr.)
		140% (4 hr.)	120% (4 hr.)
		155% (8 hr.)	120% (8 hr.)
		170% (16 hr.)	140% (16 hr.)
Cell Size	E	10 A. H.	3.5 A. H.
Discharge Rate	F	5 hr.	15 min.

* Four charge periods were divided between two (2) factors:

The high level of (B) and the low level of (C) is 8 hours
The high level of (C) and the low level of (B) is 1 hour
The high level of (B) and (C) is 16 hours
The low level of (B) and (C) is 4 hours

Figure 1 Constant Current Test Variables - Experiment I

2^{6-1} factorial

Run No.	Treatment Conditions	A	B	C	D	E	F	Response* (%)
1	(1)	-	-	-	-	-	-	70.6
2	a(f)	+	-	-	-	-	+	68.1
3	b(f)	-	+	-	-	-	+	93.6
4	ab	+	+	-	-	-	-	29.1
5	c(f)	-	-	+	-	-	+	90.3
6	ac	+	-	+	-	-	-	40.4
7	bc	-	+	+	-	-	-	40.8
8	abc(f)	+	+	+	-	-	+	67.6
9	d(f)	-	-	-	+	-	+	97.5
10	ad	+	-	-	+	-	-	40.6
11	bd	-	+	-	+	-	-	68.1
12	abd(f)	+	+	-	+	-	+	60.6
13	cd	-	-	+	+	-	-	54.7
14	acd(f)	+	-	+	+	-	+	86.8
15	bcd(f)	-	+	+	+	-	+	92.2
16	abcd	+	+	+	+	-	-	20.9
17	e(f)	-	-	-	-	+	+	85.0
18	ae	+	-	-	-	+	-	53.5
19	be	-	+	-	-	+	-	64.8
20	abe(f)	+	+	-	-	+	+	76.2
21	ce	-	-	+	-	+	-	72.9
22	ace(f)	+	-	+	-	+	+	74.4
23	bce(f)	-	+	+	-	+	+	73.8
24	abce	+	+	+	-	+	-	56.9
25	de	-	-	-	+	+	-	82.6
26	ade(f)	+	-	-	+	+	+	63.3
27	bde(f)	-	+	-	+	+	+	89.6
28	abde	+	+	-	+	+	-	50.4
29	cde(f)	-	-	+	+	+	+	94.8
30	acde	+	-	+	+	+	-	75.4
31	bcde	-	+	+	+	+	-	74.0
32	abcde(f)	+	+	+	+	+	+	72.3

+ = High Level of factor (see Fig. 1)
- = Low Level of factor (see Fig. 1)

$$* \text{ Response } (\%) = \frac{\text{Amp-Hours Output at Test Conditions}}{\text{Amp-Hours (Normalizing Cycle at Std. Conditions)}} \times 100$$

Figure 2 Experiment Design I

Run No.	Cell No.	A Temp. °F	BC Charge Period hrs.	D Overcharge %	Charge Rate Amps.	E Cell Size A.H.	F Discharge Time	Rate Amps.
1	1	75	4	120	1.050	3.5	15 min.	10.5
2	2	125	4	120	1.050	3.5	5 hr.	0.7
3	3	75	8	120	0.525	3.5	5 hr.	0.7
4	4	125	8	120	0.525	3.5	15 min.	10.5
5	5	75	1	110	3.850	3.5	5 hr.	0.7
6	6	125	1	110	3.850	3.5	15 min.	10.5
7	7	75	16	140	0.306	3.5	15 min.	10.5
8	8	125	16	140	0.306	3.5	5 hr.	0.7
9	9	75	4	140	1.225	3.5	5 hr.	0.7
10	10	125	4	140	1.225	3.5	15 min.	10.5
11	11	75	8	155	0.687	3.5	15 min.	10.5
12	12	125	8	155	0.687	3.5	5 hr.	0.7
13	13	75	1	130	4.550	3.5	15 min.	10.5
14	14	125	1	130	4.550	3.5	5 hr.	0.7
15	15	75	16	170	0.372	3.5	5 hr.	0.7
16	16	125	16	170	0.372	3.5	15 min.	10.5
17	31	75	4	120	3.00	10	5 hr.	2.0
18	32	125	4	120	3.00	10	15 min.	30.0
19	33	75	8	120	1.50	10	15 min.	30.0
20	34	125	8	120	1.50	10	5 hr.	2.0
21	35	75	1	110	11.0	10	15 min.	30.0
22	36	125	1	110	11.0	10	5 hr.	2.0
23	37	75	16	140	0.875	10	5 hr.	2.0
24	38	125	16	140	0.875	10	15 min.	30.0
25	39	75	4	140	3.50	10	15 min.	30.0
26	40	125	4	140	3.50	10	5 hr.	2.0
27	41	75	8	155	1.937	10	5 hr.	2.0
28	42	125	8	155	1.937	10	15 min.	30.0
29	43	75	1	130	13.0	10	5 hr.	2.0
30	44	125	1	130	13.0	10	15 min.	30.0
31	45	75	16	170	1.063	10	15 min.	30.0
32	46	125	16	170	1.063	10	5 hr.	2.0

Figure 3 Test Conditions Experiment I

Run No.	O.C.V. Before Charge	End of Charge Voltage	O.C.V. Before Discharge	Discharge Rate Amps.	Minutes to 1.0 Volts	Amp.-Hrs. at test Conditions	Amp.-Hrs. at Std. Conditions
1	1.24	1.46	1.37	10.5	17	2.98	4.22
2	1.25	1.38	1.31	0.7	221	2.58	3.79
3	1.24	1.44	1.35	0.7	286	3.34	3.57
4	1.24	1.35	1.31	10.5	6.5	1.14	3.92
5	1.25	1.56	1.35	0.7	263	3.07	3.40
6	1.24	1.32	1.31	10.5	8.5	1.49	3.69
7	1.24	1.43	1.37	10.5	9.5	1.66	4.07
8	1.24	1.33	1.30	10.7	216	2.52	3.73
9	1.23	1.48	1.37	0.7	335	3.91	4.01
10	1.23	1.37	1.32	10.5	9	1.57	3.87
11	1.24	1.45	1.37	0.7	16	2.80	4.11
12	1.25	1.37	1.32	0.7	214	2.49	4.11
13	1.24	1.60	1.36	10.5	13	2.27	4.15
14	1.23	1.49	1.30	0.7	300	3.50	4.03
15	1.23	1.43	1.36	0.7	303	3.54	3.84
16	1.23	1.35	1.32	10.5	4	0.81	3.87
17	1.23	1.47	1.37	2	324	10.80	12.70
18	1.24	1.38	1.30	30	12.8	6.40	11.97
19	1.23	1.44	1.34	30	16.3	8.15	12.57
20	1.22	1.35	1.28	2	281	9.37	12.30
21	1.23	1.52	1.36	30	17.2	8.60	11.80
22	1.22	1.45	1.29	2	262	8.73	11.73
23	1.23	1.42	1.35	2	273	9.10	12.33
24	1.05	1.35	1.30	30	14	7.00	12.30
25	1.24	1.52	1.36	30	20.2	10.10	12.23
26	1.20	1.32	1.28	2	233	7.77	12.27
27	1.24	1.45	1.34	2	330	11.00	12.27
28	1.24	1.37	1.29	30	11.5	5.75	11.40
29	1.24	1.70	1.34	2	331	11.02	11.63
30	1.23	1.51	1.29	30	18.7	9.35	12.40
31	1.23	1.43	1.35	30	18.5	9.25	12.50
32	1.23	1.35	1.28	2	263	8.77	12.13

Figure 4   Cell Test Data - Experiment I

Yates' Algorithm

Run No.	Response	(1)	(2)	(3)	(4)	(5)	Mean Effects (5)/16	Measured Effects
1	70.6	138.7	261.4	500.5	1021.9	2181.8	136.6	I, ABCDEF
2	68.1	122.7	239.1	521.4	1159.9	-308.8	-19.3	A, BCDEF
3	93.6	130.7	266.8	557.5	-193.7	-120.0	-7.5	B, ACDEF
4	29.1	108.4	254.6	602.4	-115.1	-17.0	-1.1	AB, CDEF
5	90.3	138.1	279.5	-90.1	-76.1	-5.4	-0.3	C, ABDEF
6	40.4	128.7	278.0	-103.6	-43.9	111.2	7.0	AC, BDEF
7	40.8	141.5	285.9	-35.5	-39.3	-62.4	-3.9	BC, ADEF
8	67.6	113.1	316.5	-79.6	22.3	-37.8	-2.4	ABC, DEF
9	97.5	138.5	-67.0	-38.3	-34.5	65.8	4.1	D, ABCEF
10	40.6	141.0	-23.1	-37.8	29.1	-57.6	-3.6	AD, BCEF
11	68.1	147.3	-64.4	-14.1	69.1	-15.2	-1.0	BD, ACEF
12	60.6	130.7	-39.2	-29.8	42.1	-95.4	-6.0	ABD, CEF
13	54.7	145.9	-20.1	14.7	-25.3	42.2	2.6	CD, ABEF
14	86.8	140.0	-15.4	-54.0	-37.1	14.0	0.9	ACD, BEF
15	92.2	170.2	-58.5	24.5	-14.1	-11.6	-0.7	BCD, AEF
16	20.9	146.3	-21.1	-2.2	-23.7	-192.6	-12.1	ABCD, EF
17	85.0	-2.5	-16.0	-22.3	20.9	138.0	8.6	E, ABCDF
18	53.5	-64.5	-22.3	-12.2	44.9	+78.6	4.9	AE, BCDF
19	64.8	-49.9	-9.4	-1.5	-13.5	32.2	2.0	BE, ACDF
20	76.2	26.8	-28.4	30.6	-44.1	61.6	3.9	ABE, CDF
21	72.9	-56.9	2.5	43.9	0.5	63.6	4.0	CE, ABDF
22	74.4	-7.5	-16.6	25.2	-15.7	-27.0	-1.7	ACE, BDF
23	73.8	32.1	-5.9	4.7	-68.7	-11.8	-0.7	BCE, ADF
24	56.9	-71.3	-23.9	37.4	-26.7	-9.6	-0.6	ABCE, DF
25	82.6	-31.5	-62.0	-6.3	10.1	24.0	1.5	DE, ABCF
26	63.3	11.4	76.7	-19.0	32.1	-30.6	-1.9	ADE, BCF
27	89.6	1.5	49.4	-19.1	-18.7	-16.2	-1.0	BDE, ACF
28	50.4	-16.9	-103.4	-18.0	32.7	42.0	2.6	ABDE, CF
29	94.8	-19.3	42.9	138.7	-12.7	22.0	1.4	CDE, ABF
30	75.4	-39.2	-18.4	-152.8	1.1	51.4	3.2	ACDE, BF
31	74.0	-19.4	-19.9	-61.3	-291.5	13.8	0.9	BCDE, AF
32	72.3	-1.7	17.7	37.6	98.9	390.4	24.4	ABCDE, F
	Checks	1873.0	1736.0	1741.6	1491.2	2313.6		
	2181.8							
	1873.0							
	1736.0							
	1741.6							
	1491.2							
	2313.6							

Figure 5 Design I Analysis

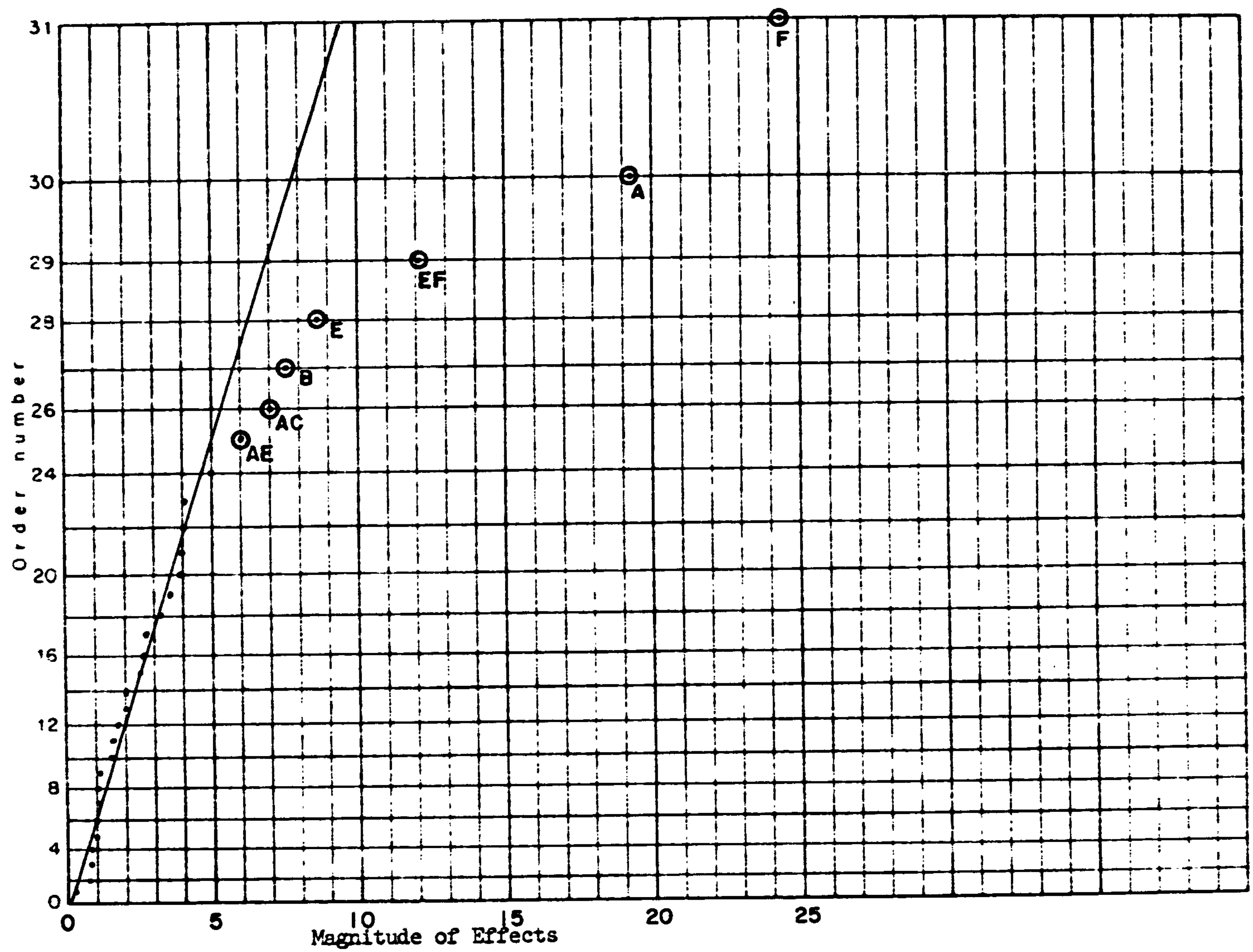


Figure 6 Half Normal Plot of Mean Effects Design I

Yates' Algorithm

Run No.	Response	Log Resp.	(1)	(2)	(3)	(4)	(5)	Measured Effects
1	70.6	.85	1.68	3.11	6.12	12.29	25.93	I, ABCDEF
2	68.1	.83	1.43	3.01	6.17	13.64	-2.23	A, BCDEF
3	93.6	.97	1.57	3.21	6.70	-1.53	-1.07	B, ACDEF
4	29.1	.46	1.44	2.96	6.94	-.70	-.31	AB, CDEF
5	90.3	.96	1.60	3.35	-.66	-.77	-.15	C, ABDEF
6	40.4	.61	1.61	3.35	-.87	-.30	.69	AC, BDEF
7	40.8	.61	1.68	3.37	-.24	-.43	-.51	BC, ADEF
8	67.6	.83	1.28	3.57	-.46	.12	-.27	ABC, DEF
9	97.5	.99	1.66	-.53	-.38	-.35	.29	D, ABCEF
10	40.6	.61	1.69	-.13	-.39	.20	-.43	AD, BCEF
11	68.1	.83	1.73	-.43	-.08	.39	-.15	BD, ACEF
12	60.6	.78	1.62	-.44	-.22	.30	-.75	ABD, CEF
13	54.7	.74	1.72	-.13	.08	-.29	.05	CD, ABEF
14	86.8	.94	1.65	-.11	-.51	-.22	-.15	ACD, BEF
15	92.2	.96	1.86	-.37	.14	-.11	-.47	BCD, AEF
16	20.9	.32	1.71	-.09	-.02	-.16	-1.59	ABCD, EF
17	85.0	.93	-0.02	-.25	-.10	.05	1.35	E, ABCDF
18	53.5	.73	-0.51	-.13	-.25	-.24	.83	AE, BCDF
19	64.8	.81	-0.35	.01	.00	-.21	.47	BE, ACDF
20	76.2	.88	0.22	-.40	.20	-.22	.55	ABE, CDF
21	72.9	.86	-0.38	.03	.40	-.01	.55	CE, ABDF
22	74.4	.87	-.05	-.11	-.01	-.14	-.09	ACE, BDF
23	73.8	.87	.20	-.07	.02	-.59	.07	BCE, ADF
24	56.9	.75	-.64	-.15	.28	-.16	-.05	ABCE, DF
25	82.6	.92	-.20	-.49	.12	-.15	.19	DE, ABCF
26	63.3	.80	.07	.57	-.41	.20	-.01	ADE, BCF
27	89.6	.95	.01	.33	-.14	-.41	-.13	BDE, ACF
28	50.4	.70	-.12	-.84	-.08	.26	.43	ABDE, CF
29	94.8	.98	-.12	.27	1.06	-.53	.35	CDE, ABF
30	75.4	.88	-.25	-.13	-1.17	.06	.67	ACDE, BF
31	74.0	.85	-.10	-.13	- .40	-2.23	.59	BCDE, AF
32	72.3	.86	.01	.11	.24	.64	2.87	ABCDE, F
		Checks	23.70	22.32	22.08	18.88	27.52	
		25.93						
		23.70						
		22.32						
		22.08						
		18.88						
		27.52						

Figure 7 Design I Analysis Using Logarithms

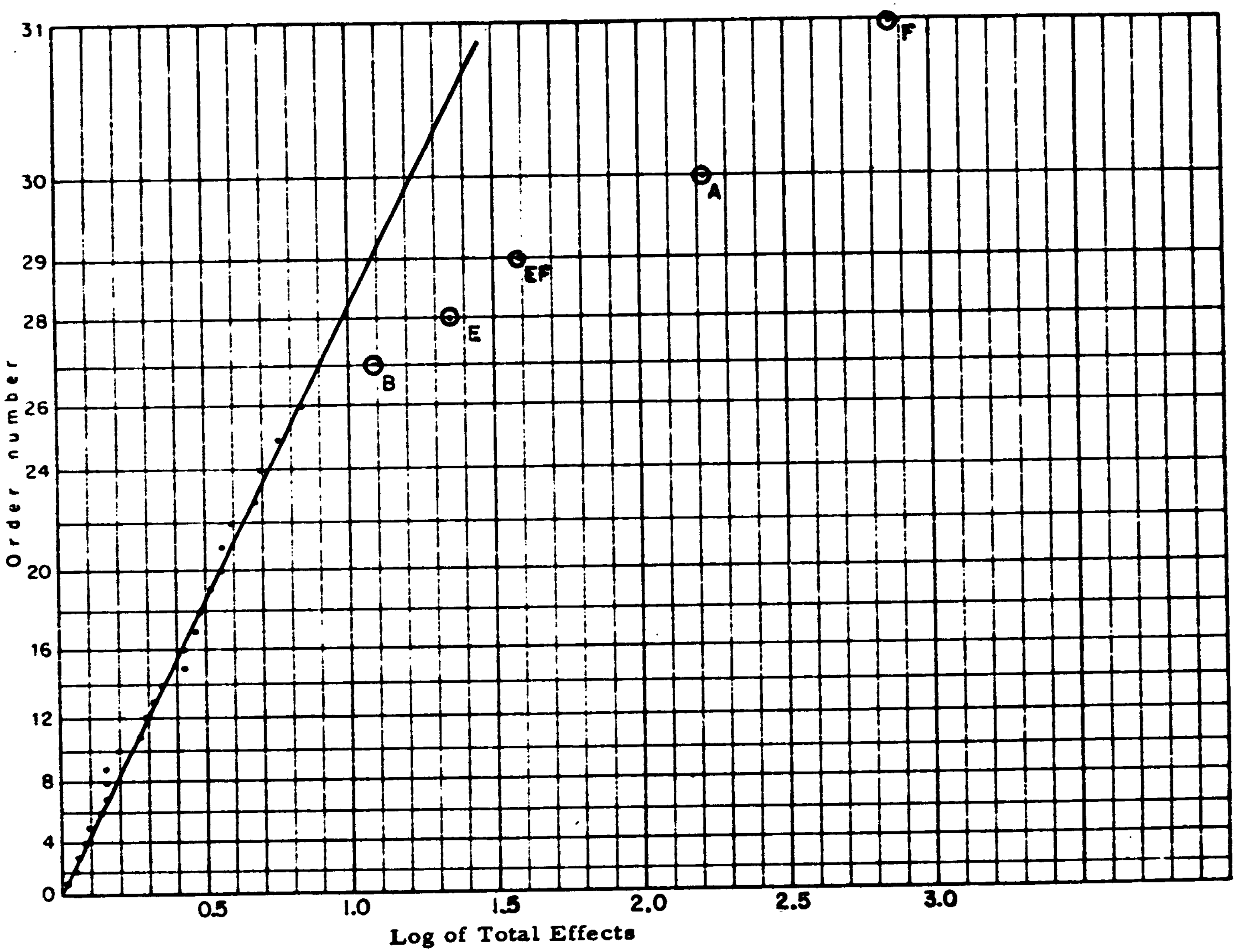


Figure 8 - Half Normal plot of Logarithms of Total Effects

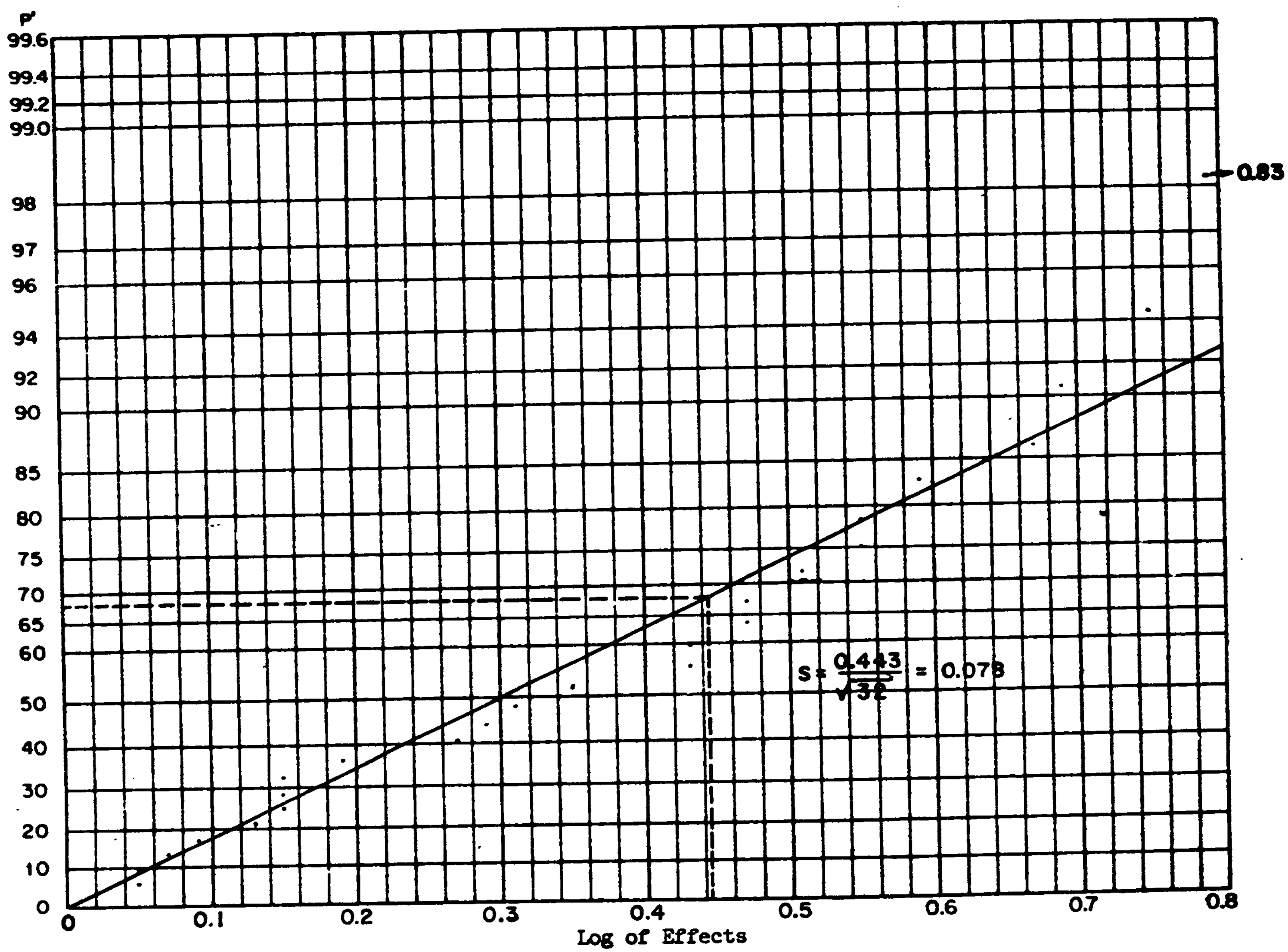


Figure 9 Half Normal plot of lower twenty-six effects to obtain Standard error

Reverse Yates'

Run No.	Measured Effects	(5)	(5')	(6')	(7')	(8')	(9')	(10')	Predicted Log of Response
1	I	25.93	25.93	28.16	29.23	29.23	27.64	23.42	.732
2	A	-2.23	-2.23	-1.07	0	1.59	+4.22	27.88	.871
3	B	-1.07	-1.07	0	0	1.35	26.36	30.20	.944
4	-	-.31	0	0	-1.59	-2.87	-1.52	16.82	.526
5	-	-.15	0	0	1.35	24.77	28.68	32.34	1.011
6	-	.69	0	0	0	-1.59	-1.52	18.96	.592
7	-	-.51	0	0	0	1.35	21.04	21.28	.665
8	-	-.27	0	1.59	2.87	2.87	4.22	25.74	.804
9	-	.29	0	1.35	24.77	27.09	30.82	32.34	1.011
10	-	-.43	0	0	0	-1.59	-1.52	18.96	.592
11	-	-.15	0	0	0	1.35	23.18	21.28	.665
12	-	-.75	0	0	1.59	2.87	4.22	25.74	.804
13	-	.05	0	0	1.35	22.63	25.50	23.42	.732
14	-	-.15	0	0	0	1.59	4.22	27.88	.871
15	-	-.47	0	0	0	1.35	24.22	30.20	.944
16	EF	-1.59	-1.59	-2.87	-2.87	-2.87	-1.52	16.82	.526
17	E	1.35	1.35	23.70	27.09	29.23	30.82	31.86	.996
18	-	.83	0	-1.07	0	-1.59	-1.52	24.84	.776
19	-	.47	0	0	0	1.35	23.18	27.16	.849
20	-	.55	0	0	1.59	2.87	4.22	25.26	.789
21	-	.55	0	0	1.35	24.77	25.50	29.30	.916
22	-	-.09	0	0	0	1.59	4.22	27.40	.856
23	-	.07	0	0	0	1.35	24.22	29.72	.929
24	-	-.05	0	-1.59	-2.87	-2.87	-1.52	22.70	.709
25	-	.19	0	1.35	22.63	27.09	27.64	29.30	.916
26	-	-.01	0	0	0	1.59	4.22	27.40	.856
27	-	-.13	0	0	0	1.35	26.36	29.72	.929
28	-	.43	0	0	-1.59	-2.87	-1.52	22.70	.709
29	-	.35	0	0	1.35	22.63	28.68	31.86	.996
30	-	.67	0	0	0	-1.59	-1.52	24.84	.776
31	-	.59	0	0	0	1.35	21.04	27.16	.849
32	F	2.87	2.87	2.87	2.87	2.87	4.22	25.26	.789

Computation for thirty-two predicted responses is made on the assumption that all effects are zero except for I (average), and the controlling factors F, E, EF, A, and B.

Figure 10 Reverse Yates' Algorithm Design I

Run No.	Log of Observed Response	Predicted Log of Response	Observed-Predicted	Order Series
1	.85	.73	.12	-.20
2	.83	.87	-.04	-.07
3	.97	.94	.03	-.06
4	.46	.53	-.07	-.06
5	.96	1.01	-.05	-.06
6	.61	.59	.02	-.06
7	.61	.66	-.05	-.05
8	.83	.80	.03	-.05
9	.99	1.01	-.02	-.05
10	.61	.59	.02	-.04
11	.83	.66	.17	-.04
12	.78	.80	-.02	-.02
13	.74	.73	.01	-.02
14	.94	.87	.07	-.01
15	.96	.94	.02	-.01
16	.32	.52	-.20	.00
17	.93	.99	-.06	.00
18	.73	.78	-.05	.01
19	.81	.85	-.04	.01
20	.88	.79	.09	.02
21	.86	.92	-.06	.02
22	.87	.86	.01	.02
23	.87	.93	-.06	.02
24	.75	.71	.04	.03
25	.92	.92	.00	.03
26	.80	.86	-.06	.04
27	.95	.93	.02	.07
28	.70	.71	-.01	.07
29	.98	.99	-.01	.09
30	.88	.78	.10	.10
31	.85	.85	.00	.12
32	.86	.79	.07	.17

Figure 11 Comparison of Observed and Predicted Responses Design I

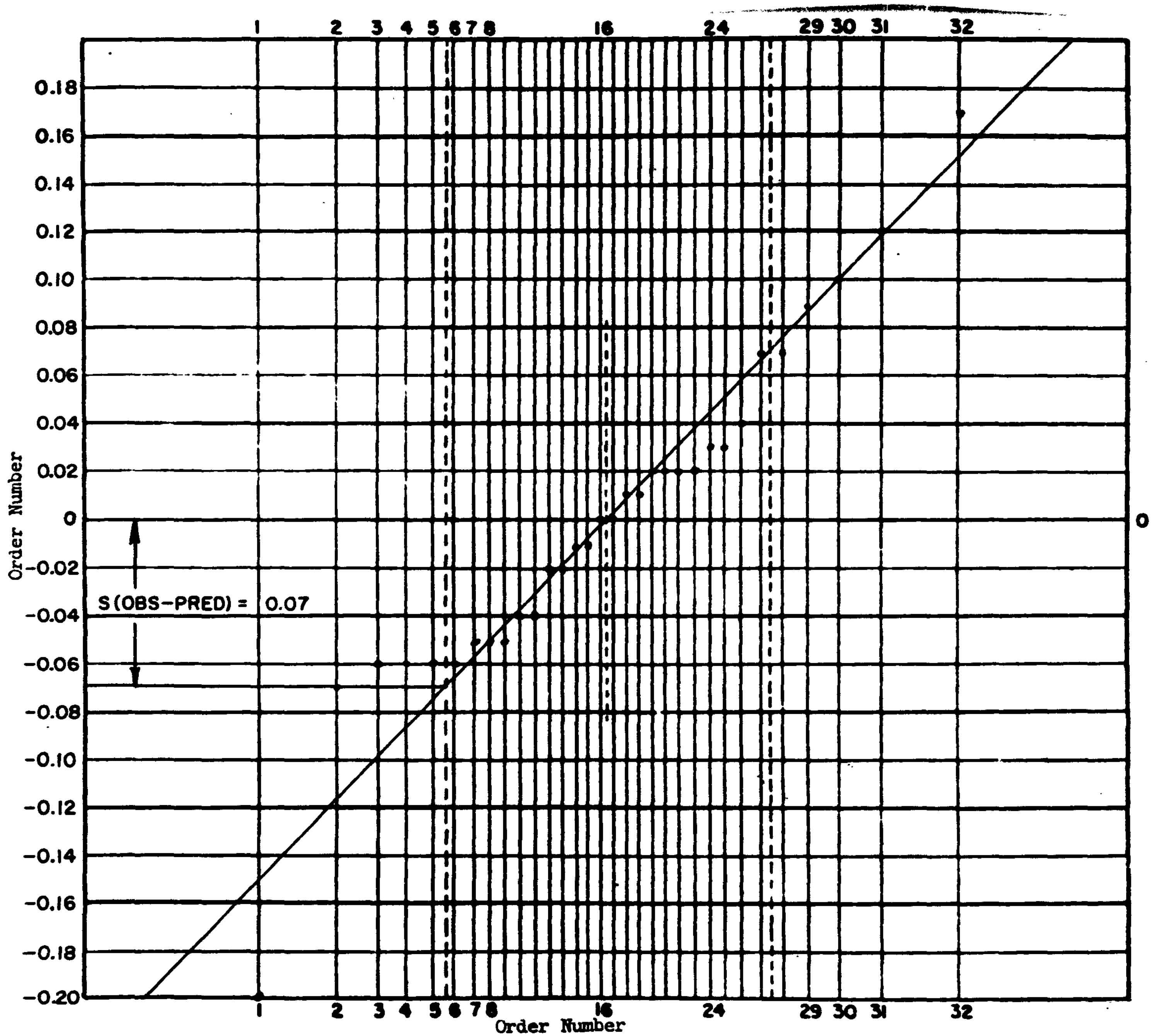


Figure 12 Plot of observed-predicted responses to obtain standard error

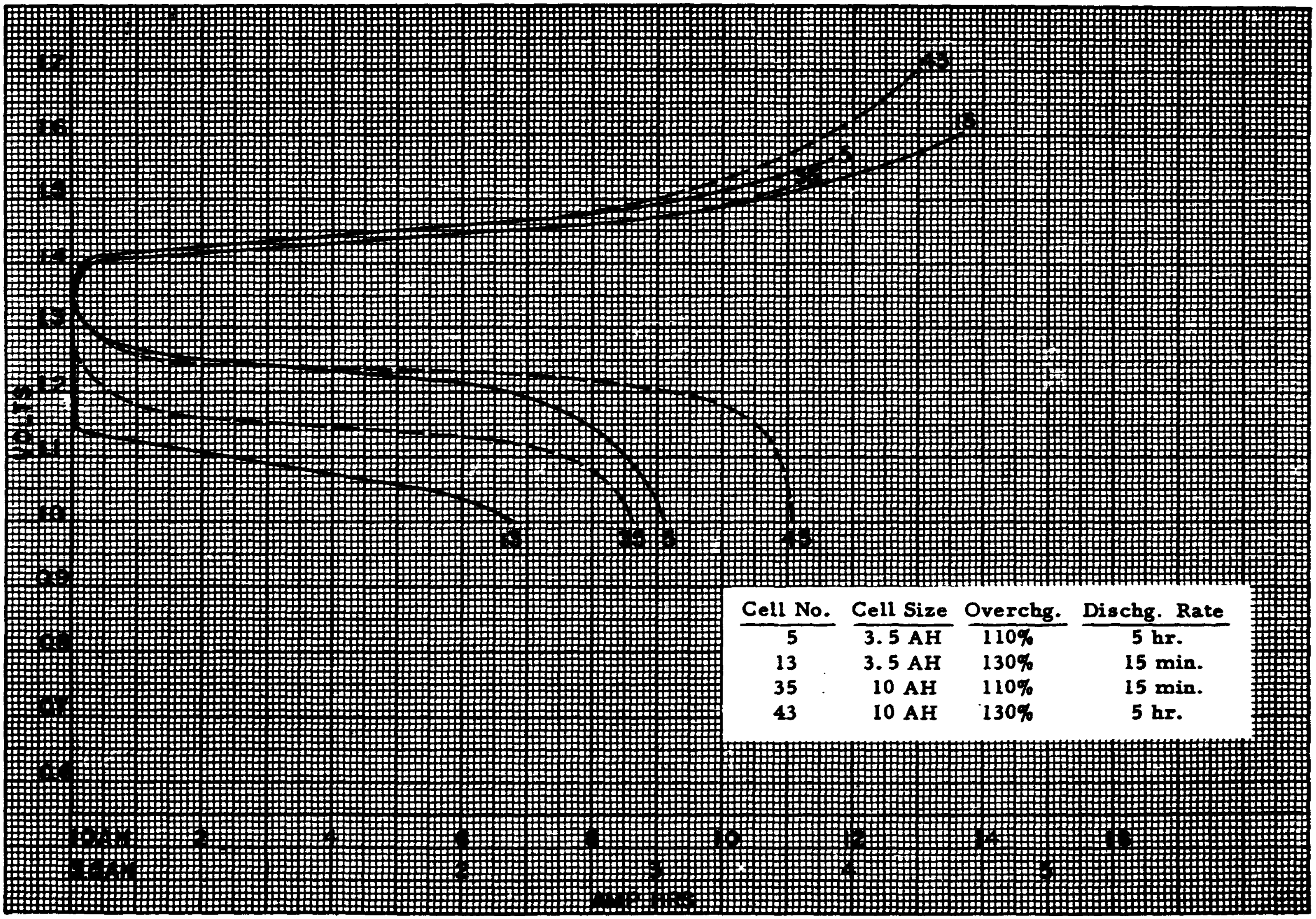


Figure 13 Charge and Discharge Characteristics (1 hr. chg. at 75°F)

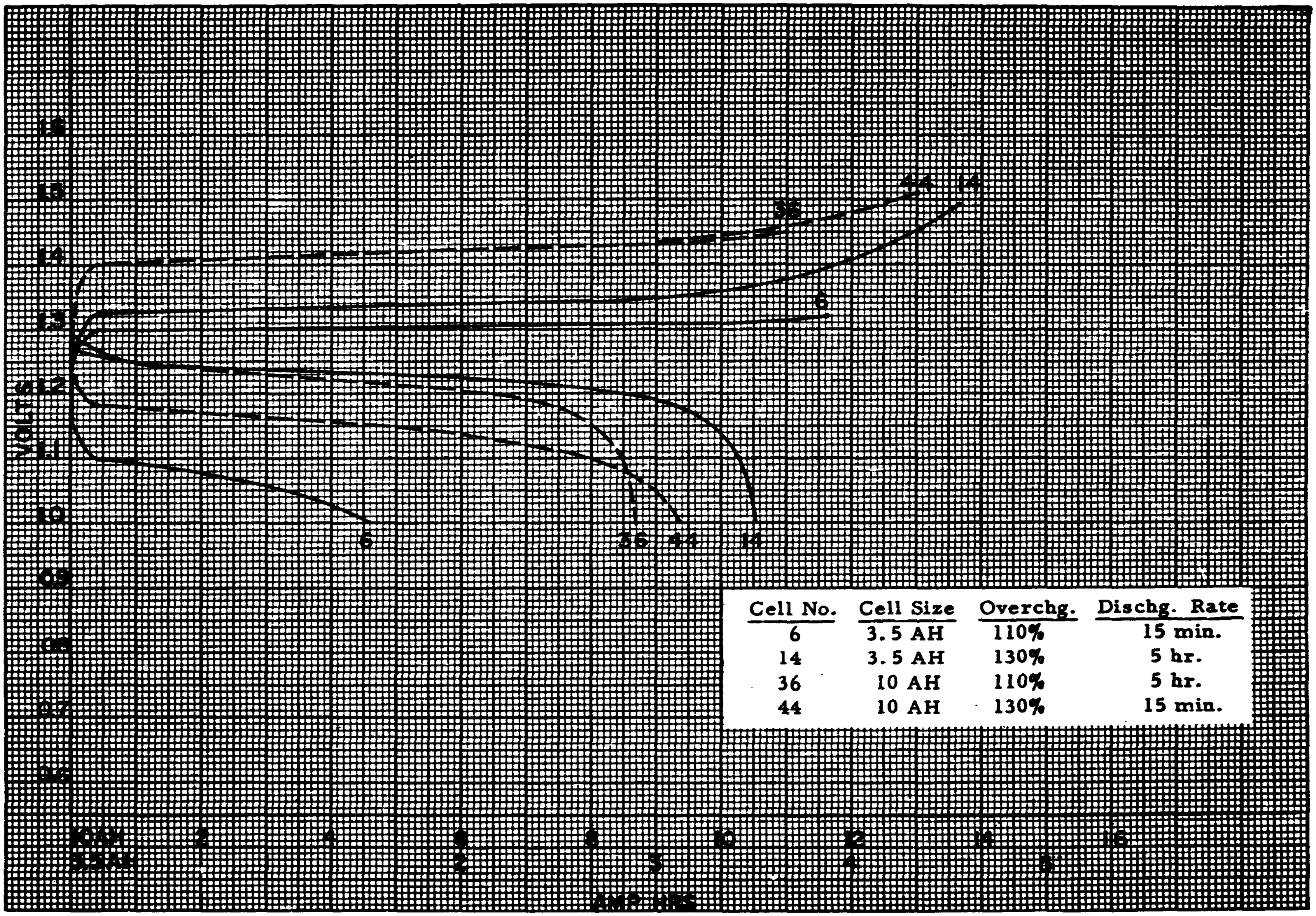


Figure 14 Charge and Discharge Characteristics (1 hr. chg. at 125°F)

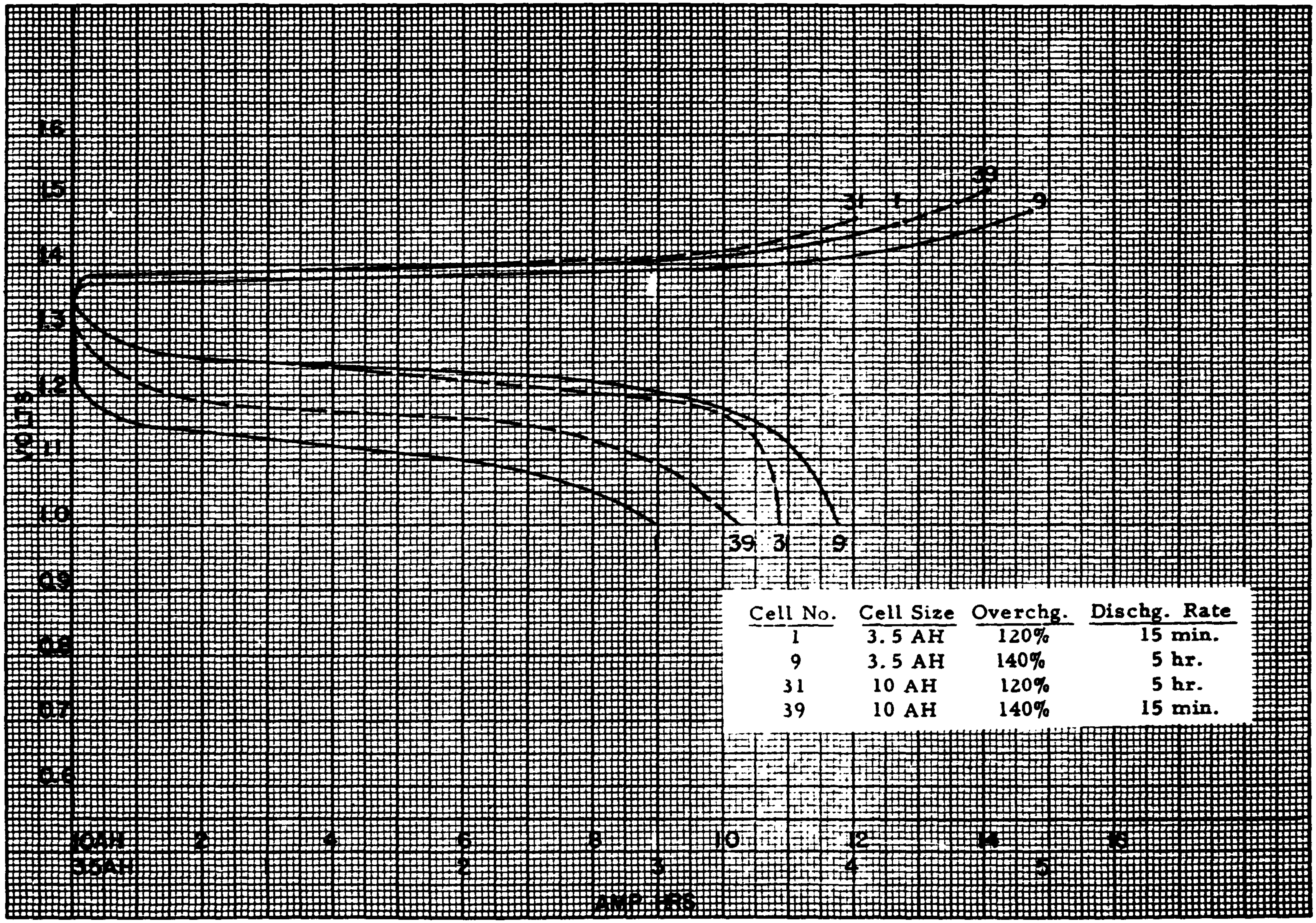
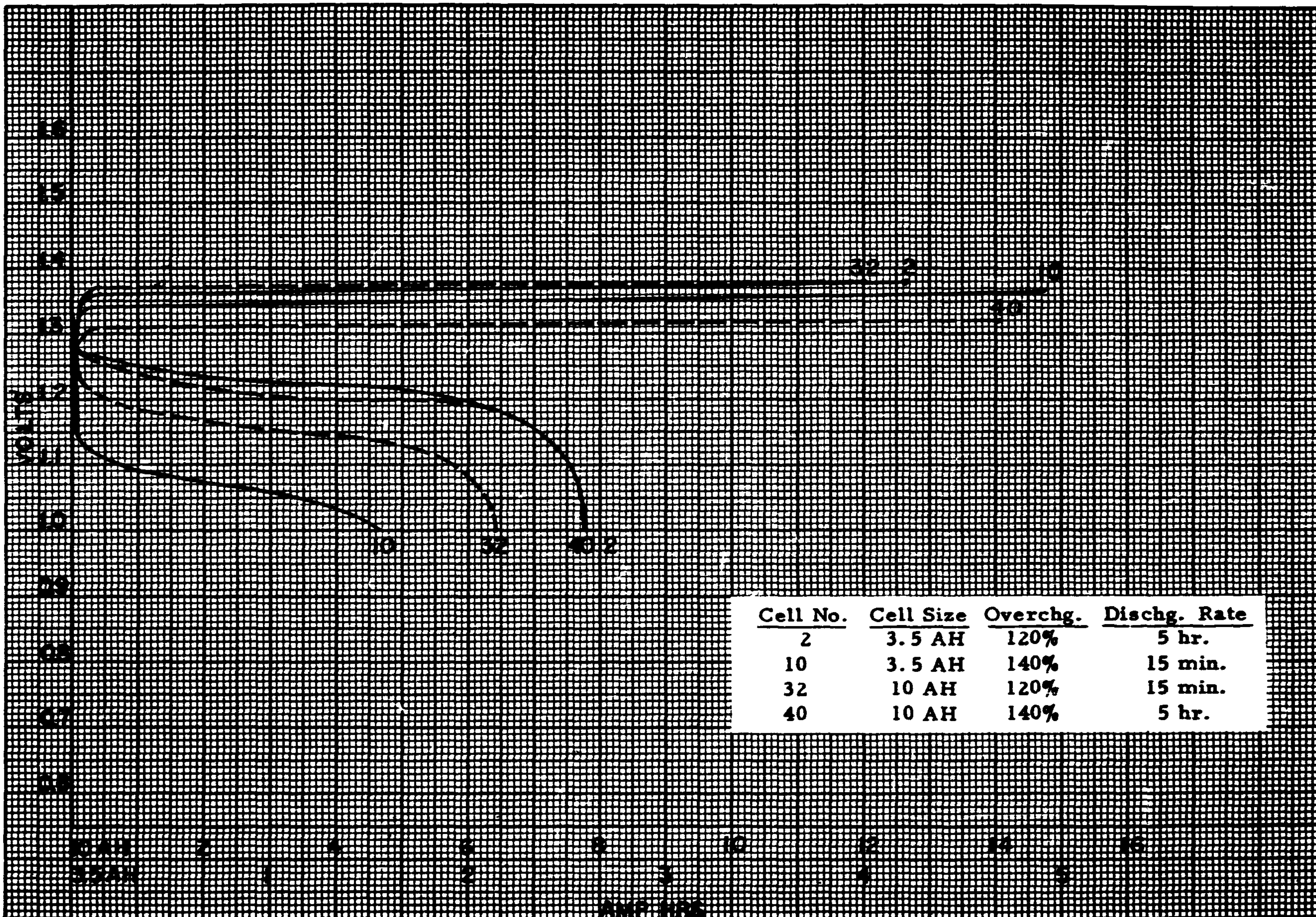


Figure 15 Charge and Discharge Characteristics (4 hr. chg. at 75°F)



Cell No.	Cell Size	Overchg.	Dischg. Rate
2	3.5 AH	120%	5 hr.
10	3.5 AH	140%	15 min.
32	10 AH	120%	15 min.
40	10 AH	140%	5 hr.

Figure 16 Charge and Discharge Characteristics (4 hr. chg. at 125°F)

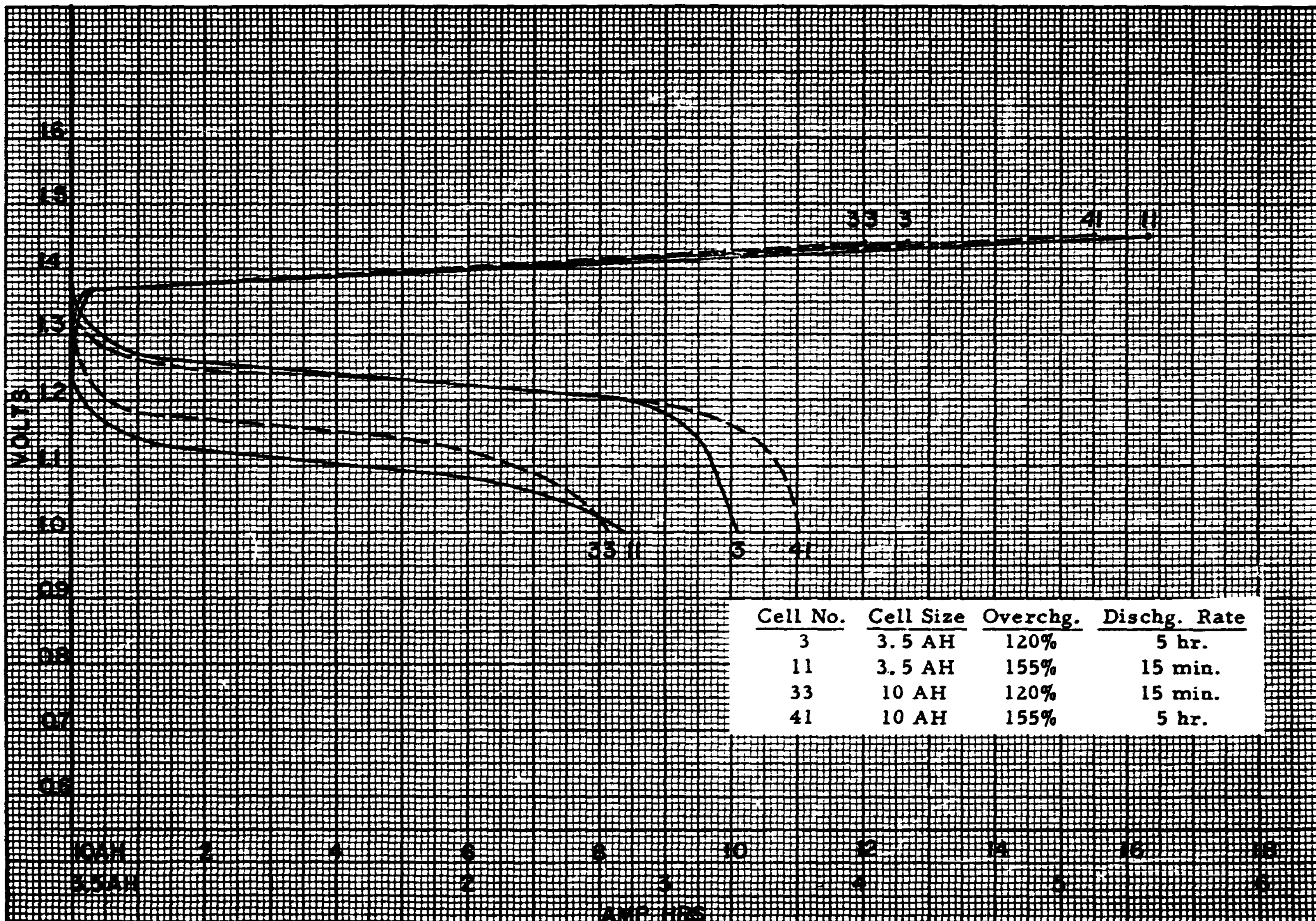
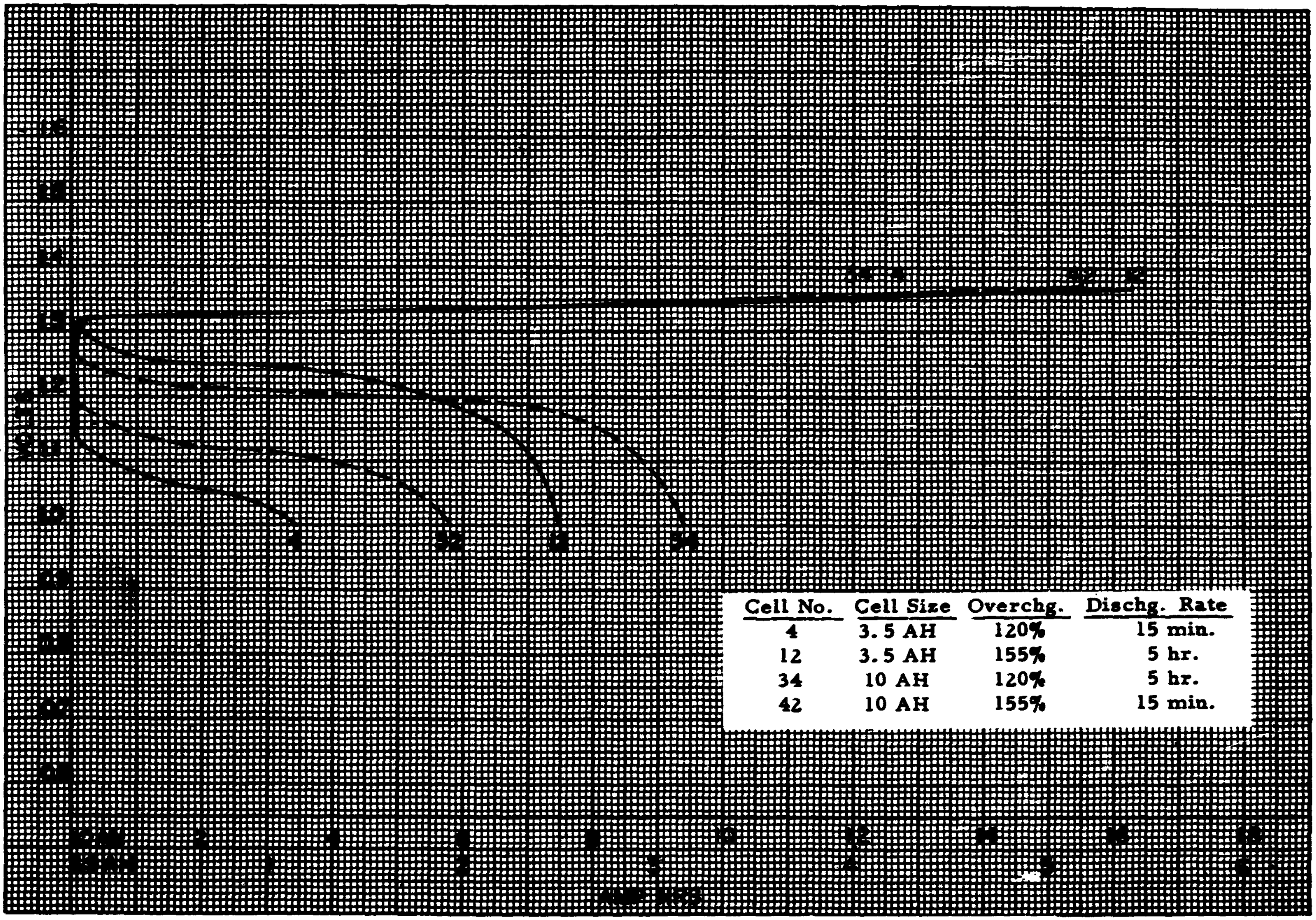


Figure 17 Charge and Discharge Characteristics (8 hr. chg. at 75°F)



Cell No.	Cell Size	Overchg.	Dischg. Rate
4	3.5 AH	120%	15 min.
12	3.5 AH	155%	5 hr.
34	10 AH	120%	5 hr.
42	10 AH	155%	15 min.

Figure 18 Charge and Discharge Characteristics (8 hr. chg. at 125°F)

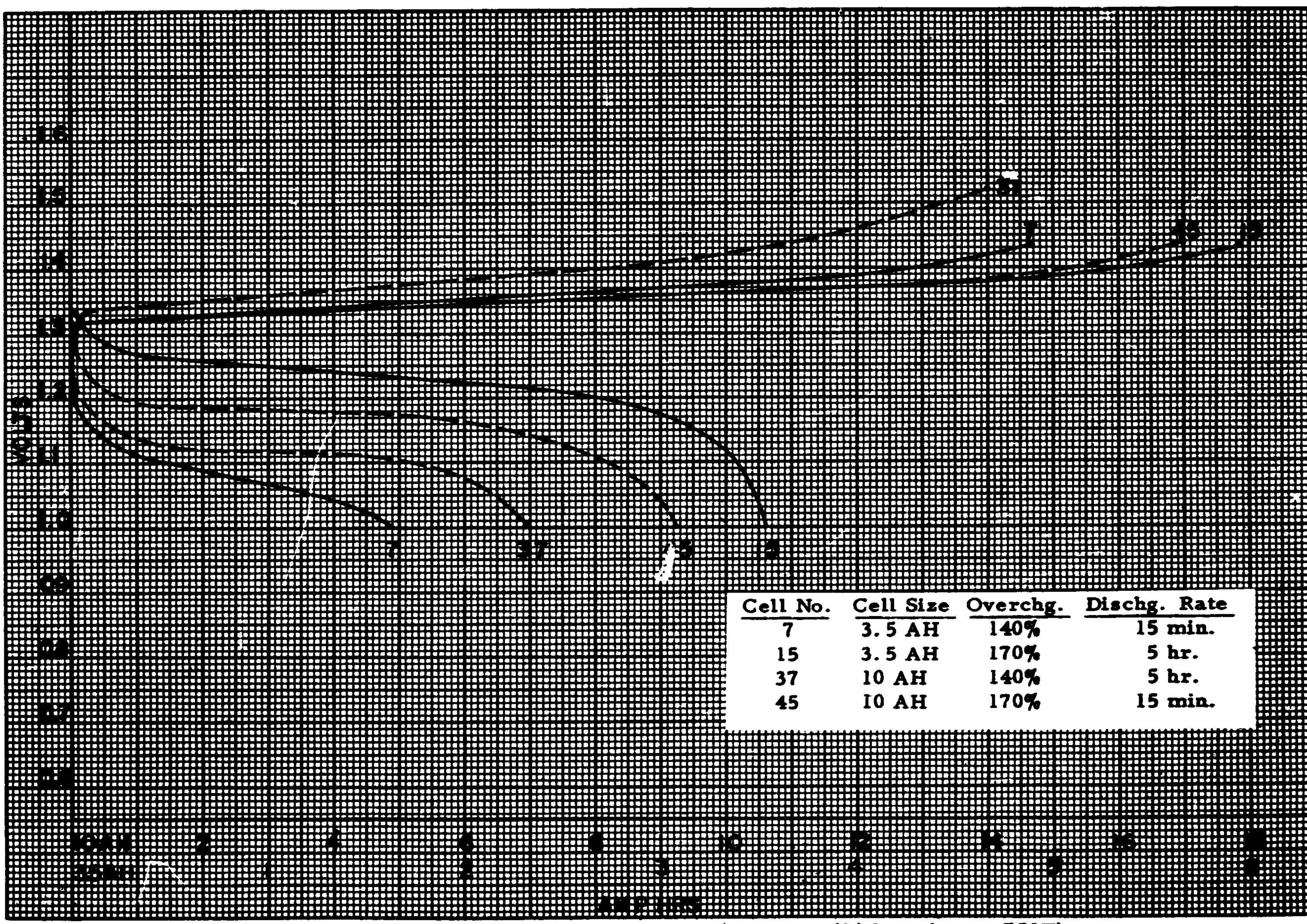


Figure 19 Charge and Discharge Characteristics (16 hr. chg. at 75°F)

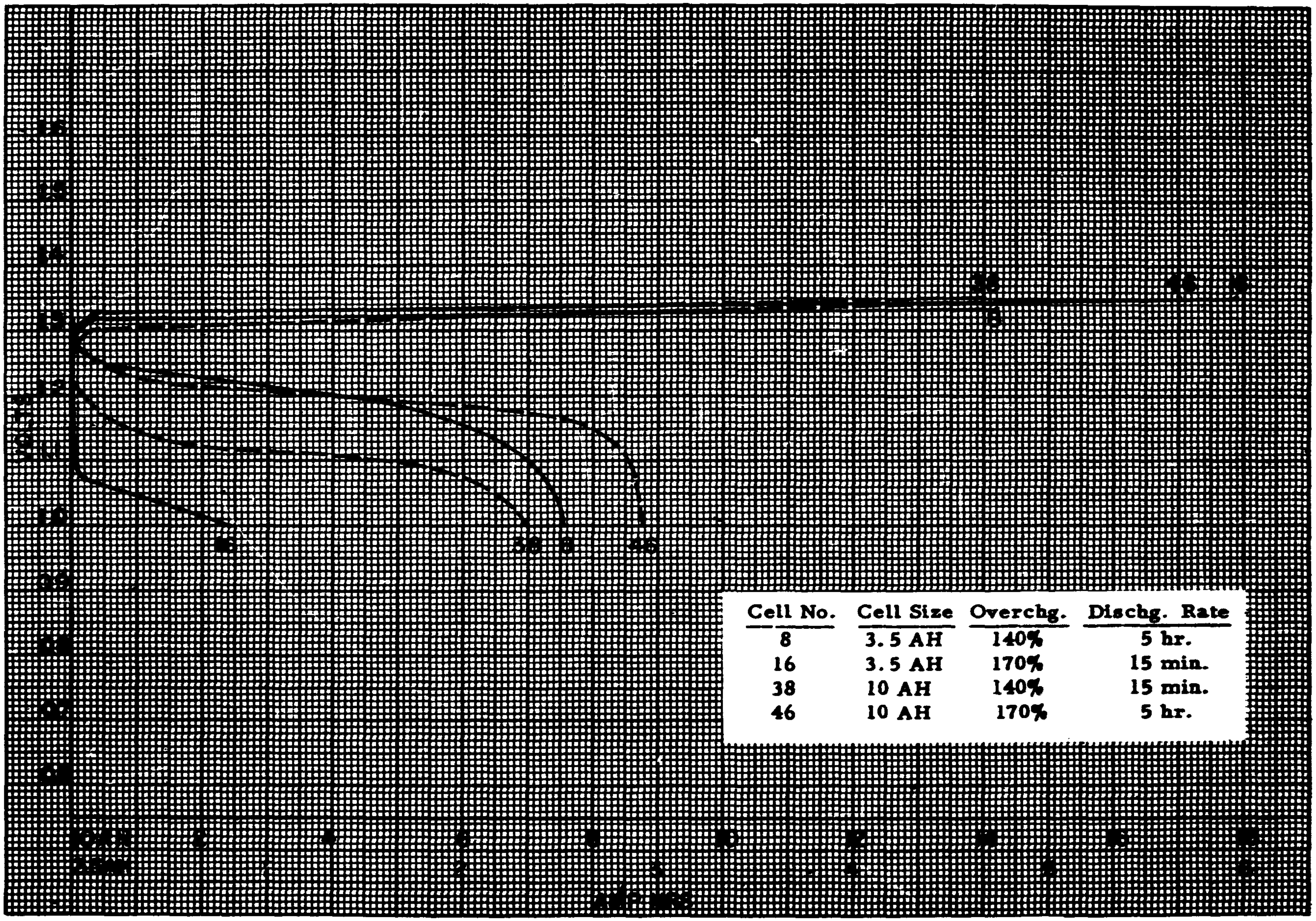


Figure 20 Charge and Discharge Characteristics (16 hr. chg. at 125°F)

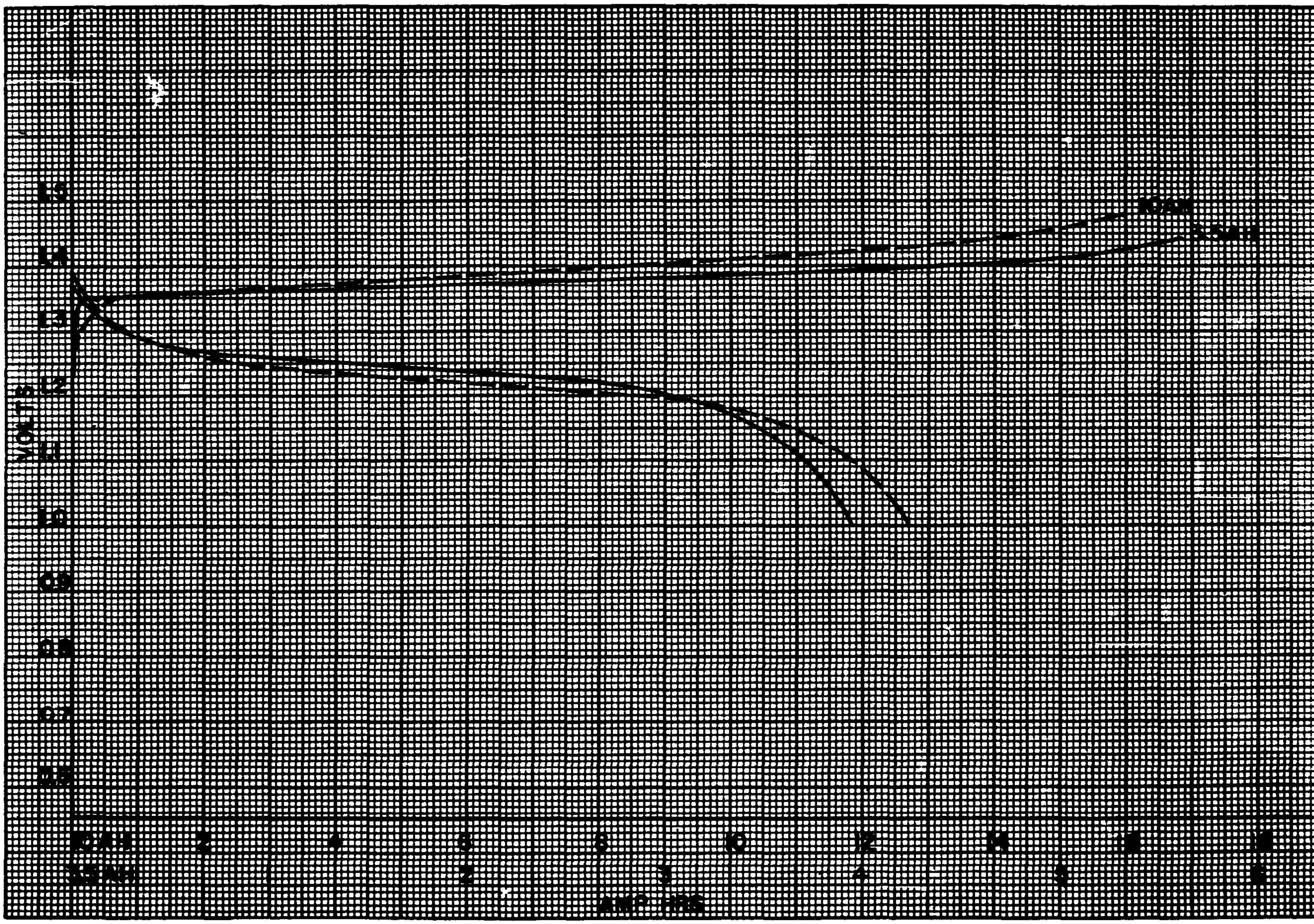


Figure 21 Typical Charge and Discharge Characteristics Normalizing Cycle

2. Charging at -10°F and -40°F (Design II)

The variables of the design for the charging tests at -10°F and -40°F were limited to five and are shown in Figure 22. Since the cells have a high internal resistance at low temperatures and to prevent damage to the cells caused by thermal heating and evolution of gas it was decided to limit the charge period to sixteen hours. Since charge period was not a variable, it was decided to substitute cell usage as a factor in this experiment design. The high level of the factor U was a new cell which has not been subjected to an experimental test. The low level of the factor U was a used cell which had been subjected to a test in Experiment I. The levels of the remaining factors are the same as Experiment I except that the high and low level of the factor F (discharge rate) was reversed.

With the variables and their levels established, the 2^{5-1} factorial design was prepared as shown in Figure 23. The design has five factors, each at two levels, and incorporates sixteen individual cells. The factor F was introduced in the same manner as that of Experiment I.

The design of the experiment in terms of the test conditions for each cell is shown in Figure 24. The cells were equipped with leads and thermocouples and prepared for test

in the same manner as the cells for the Design I tests. Prior to the experimental test runs, the cells were subjected to the normalizing charge-discharge cycle with the discharge continued to an end voltage of 0.6 volt for each cell. The cells were then stabilized at the test temperatures and tested individually at the controlled conditions of the experiment (figure 15). An open-circuit stand period of one hour was maintained between completion of 16-hour charge period and the start of discharge. Discharge and charge were performed at the same ambient temperature. To prevent possible damage to the cells, the charge potential was limited to 1.8 volts per cell. Also, since the discharge voltage plateau for the high rate discharge at the lower temperature could be less than 1.0 volt, the time to 1.0 volt and 0.6 volt was recorded. These test data are shown in Figures 25 and 26. The ampere-hour output to an end-voltage of 0.6 volt was used to determine the percent response used in the analysis for this experiment.

A Yates' Algorithm was performed for the sixteen responses obtained in the trials of the Design II experiment in the same manner as described for the Design I experiment. The computations for this analysis and the mean effects obtained are shown in Figure 27. These mean effects, not in-

cluding the twice the average figure, were then arranged in order of magnitude without regard to sign and plotted on a fifteen-factor, half-normal plot as shown in Figure 28. The effects F, A and EF fall significantly off the error best straight line determined by the twelve lower magnitude effects, and these (F, A, and EF) were judged to be the controlling factors in this experiment.

The results of the analysis again show that temperature, discharge rate and cell size in terms of discharge were controlling factors for the levels selected. The mean effect of A (temperature) is positive, indicating that better performance can be obtained at the higher temperature level of -10°F. The average response of the cells at -10°F was 70.4% compared to an average response of 58.3% at -40°F. Also, the mean effect of F (discharge rate) is minus, indicating that the best capacity output can be obtained at the low level or five-hour discharge rate. The average response for all cells at the five-hour rate was 80.5% compared to an average response of 48.2% at the fifteen-minute rate.

Again, the 10 A-H cells performed better than the smaller cells at the higher discharge current, pointing out the difference in cell design. The larger cells had an average

response of 55.2% at the 15-minute rate compared to an average of 41.2% for the 3.5 A-H cells.

The overcharge (D) for the ranges selected was not a controlling factor in this experiment. Also, the difference between cells used in Experiment Design I and the new cells was not a significant factor in this experiment. This is not unexpected since the cells of Experiment I were subjected to only one experimental test cycle and one additional normalizing cycle than the cells identified as new cells.

Charge and discharge voltage characteristics versus ampere-hours for the 16 test runs performed in Experiment II for fully discharged cells are shown in Figures 29 through 32.

Variable	Factor	Level of Factor	
		High	Low
Temperature	A	-10°F	-40°F
Cell Usage	U	new	used
Overcharge	D	170%	140%
Cell Size	E	10 A. H.	3. 5 A. H.
Discharge Rate	F	15 min.	5 hr.

Figure 22 Constant Current Test Variables - Experiment II

2^{5-1} factorial

Run No.	Treatment Conditions	Variables A	U	D	E	F	Response* %
1	1(f)	-	-	-	-	+	40.0
2	a	+	-	-	-	-	91.0
3	u	-	+	-	-	-	75.5
4	au(f)	+	+	-	-	+	43.8
5	d	-	-	+	-	-	81.4
6	ad(f)	+	-	+	-	+	50.4
7	ud(f)	-	+	+	-	+	30.6
8	aud	+	+	+	-	-	86.4
9	e	-	-	-	+	-	64.3
10	ae(f)	+	-	-	+	+	54.3
11	ue(f)	-	+	-	+	+	55.8
12	aue	+	+	-	+	-	83.5
13	de(f)	-	-	+	+	+	49.6
14	ade	+	-	+	+	-	92.4
15	ude	-	+	+	+	-	69.3
16	aude(f)	+	+	+	+	+	61.1

+ = High Level of factor
- = Low Level of factor

$$\text{* Response (\%)} = \frac{\text{Amp.-Hour Output at Test Conditions}}{\text{Amp.-Hours (Normalizing Cycle at Std. Conditions)}} \times 100$$

Figure 23 Experiment Design II

Run No.	Cell No.	Charge Period hours	A Temp. °F	B Cell Usage	D Overcharge %	Charge Rate Amps.	E Cell Size A.H.	F Discharge Time	Rate Amps.
1	1	16	-40	U	140	0.306	3.5	15 min.	10.5
2	2	16	-10	U	140	0.306	3.5	5 hr.	0.7
3	17	16	-40	N	140	0.306	3.5	5 hr.	0.7
4	18	16	-10	N	140	0.306	3.5	15 min.	10.5
5	9	16	-40	U	170	0.372	3.5	5 hr.	0.7
6	10	16	-10	U	170	0.372	3.5	15 min.	10.5
7	21	16	-40	N	170	0.372	3.5	15 min.	10.5
8	20	16	-10	N	170	0.372	3.5	5 hr.	0.7
9	31	16	-40	U	140	0.875	10	5 hr.	2.0
10	32	16	-10	U	140	0.875	10	15 min.	30.0
11	47	16	-40	N	140	0.875	10	15 min.	30.0
12	48	16	-10	N	140	0.875	10	5 hr.	2.0
13	39	16	-40	U	170	1.063	10	15 min.	30.0
14	40	16	-10	U	170	1.063	10	5 hr.	2.0
15	49	16	-40	N	170	1.063	10	5 hr.	2.0
16	50	16	-10	N	170	1.063	10	15 min.	30.0

U - Cell used in Experiment I
N - New Cell

Figure 24 Test Conditions - Experiment II

Run No.	O.C.V. Before Charge	End of Charge Voltage	O.C.V. Before Discharge	Discharge Rate Amps.	Minutes to 1.0 Volts	Amp.-Hrs. at test Conditions	Amp.-Hrs. at Std. Conditions
1	1.22	1.73	1.53	10.5	0.5	0.09	4.47
2	1.26	1.70	1.45	0.7	280	3.27	3.91
3	1.25	1.80	1.46	0.7	166	1.94	4.00
4	1.25	1.72	1.44	10.5	2.0	0.35	4.00
5	1.21	1.80	1.52	0.7	157	1.83	3.97
6	1.25	1.79	1.49	10.5	1.0	0.17	3.65
7	1.29	1.80	1.49	10.5	0.1	0.02	4.15
8	1.23	1.80	1.49	0.7	297	3.47	4.27
9	1.25	1.79	1.48	2	197	6.56	11.97
10	1.26	1.80	1.44	30	11	5.50	11.50
11	1.27	1.80	1.46	30	0.25	0.13	12.10
12	1.23	1.80	1.50	2	225	7.50	11.77
13	1.25	1.80	1.47	30	0.5	0.25	11.60
14	1.22	1.80	1.47	2	307	10.23	11.90
15	1.22	1.75	1.47	2	190	6.23	10.83
16	1.27	1.80	1.47	30	13	6.50	12.27

Figure 25 Cell Test Data Experiment II Capacity to 1.0 Volts

Run No.	O.C.V. Before Charge	End of Charge Voltage	O.C.V. Before Discharge	Discharge Rate Amps.	Minutes to 0.6 Volts	Amp.-Hrs. of test Conditions	Amp.-Hrs. of Std. Conditions
1	1.22	1.73	1.53	10.5	10.25	1.79	4.47
2	1.26	1.70	1.45	0.7	305	3.56	3.91
3	1.25	1.80	1.46	0.7	259	3.02	4.00
4	1.25	1.72	1.44	10.5	10.0	1.75	4.00
5	1.21	1.80	1.52	0.7	277	3.23	3.97
6	1.25	1.79	1.49	10.5	10.5	1.84	3.65
7	1.29	1.80	1.49	10.5	7.25	1.27	4.15
8	1.23	1.80	1.49	0.7	316	3.69	4.27
9	1.25	1.79	1.48	2	231	7.70	11.97
10	1.26	1.80	1.44	30	12.5	6.25	11.50
11	1.27	1.80	1.46	30	13.5	6.75	12.10
12	1.23	1.80	1.50	2	295	9.83	11.77
13	1.25	1.80	1.47	30	11.5	5.75	11.60
14	1.22	1.80	1.47	2	330	11.00	11.90
15	1.22	1.75	1.47	2	225	7.50	10.83
16	1.27	1.80	1.47	30	15.0	7.50	12.27

Figure 26 Cell Test Data Experiment II Capacity to 0.6 Volts

Note: Charges for Runs No. 3, 10, 11, and 12 (initiated for 140%) ranged from 128 to 137%.
Charges for Runs No. 5, 7, 8, 13, 14 and 16 (initiated for 170%) ranged from 150 to 160%.

Yates' Algorithm

Run No.	Response	(1)	(2)	(3)	(4)	Mean Effects (4)/8	Measured Effects
1	40.0	131.0	250.3	499.1	1029.4	128.7	I (AUDEF)
2	91.0	119.3	248.8	530.3	96.4	12.1	A, UDEF
3	75.5	131.8	257.9	44.1	-17.4	-2.2	U, ADEF
4	43.8	117.0	272.4	52.3	-9.2	-1.2	AU, DEF
5	81.4	118.6	19.3	-26.5	13.0	1.6	D, AUEF
6	50.4	139.3	24.8	9.1	22.4	2.8	AD, UEF
7	30.6	142.0	17.7	4.1	-35.4	-4.4	UD, AEF
8	86.4	130.4	34.6	-13.3	80.8	10.1	AUD, EF
9	64.3	51.0	-11.7	-1.5	31.2	3.9	E, AUDF
10	54.3	-31.7	-14.8	14.5	8.2	1.0	AE, UDF
11	55.8	-31.0	20.7	5.5	35.6	4.5	UE, ADF
12	83.5	55.8	-11.6	16.9	-17.4	-2.2	AUE, DF
13	49.6	-10.0	-82.7	-3.1	16.0	2.0	DE, AUF
14	92.4	27.7	86.8	-32.3	11.4	1.4	ADE, UF
15	69.3	42.8	37.7	169.5	-29.2	-3.7	UDE, AF
16	61.1	-8.2	-51.0	-88.7	-258.2	-32.3	(AUDE), F
	Checks	1125.8	1099.2	1180.0	997.6		

Checks
1029.4
1125.8
1099.2
1180.0
977.6

Figure 27 Design II Analysis

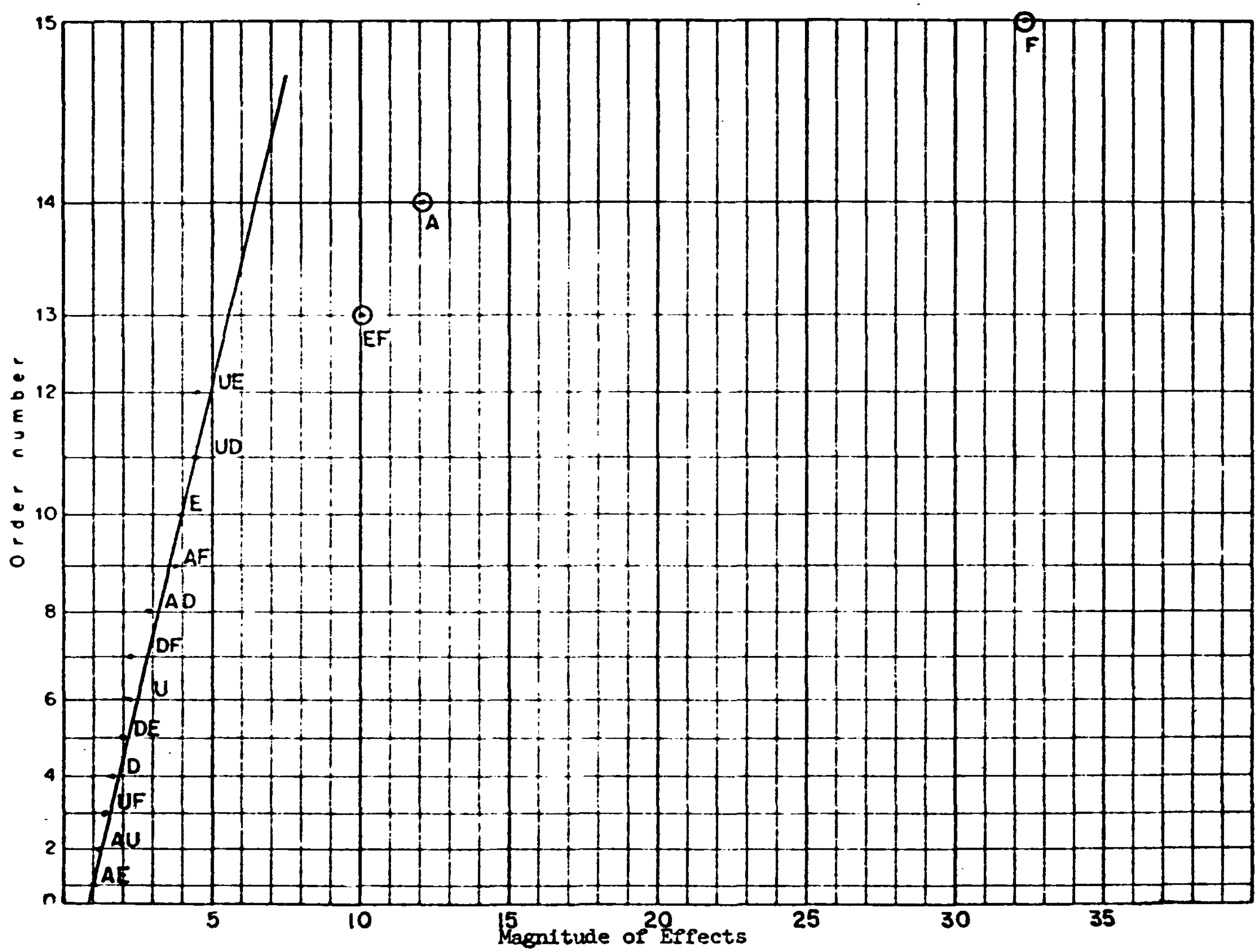
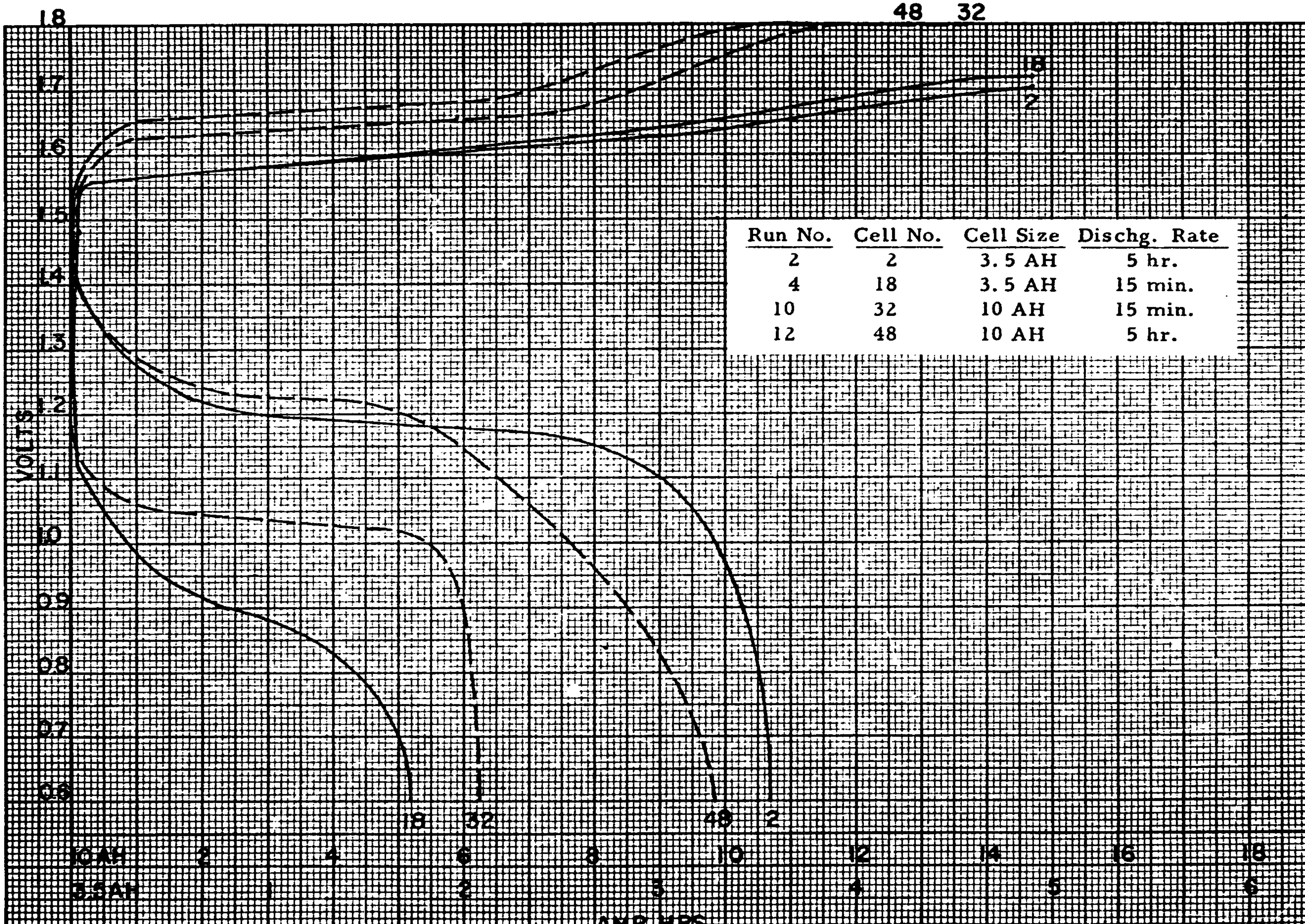


Figure 28 Half Normal plot of Mean Effects Design II



Run No.	Cell No.	Cell Size	Dischg. Rate
2	2	3.5 AH	5 hr.
4	18	3.5 AH	15 min.
10	32	10 AH	15 min.
12	48	10 AH	5 hr.

Figure 29 Charge and Discharge Characteristics at -10°F

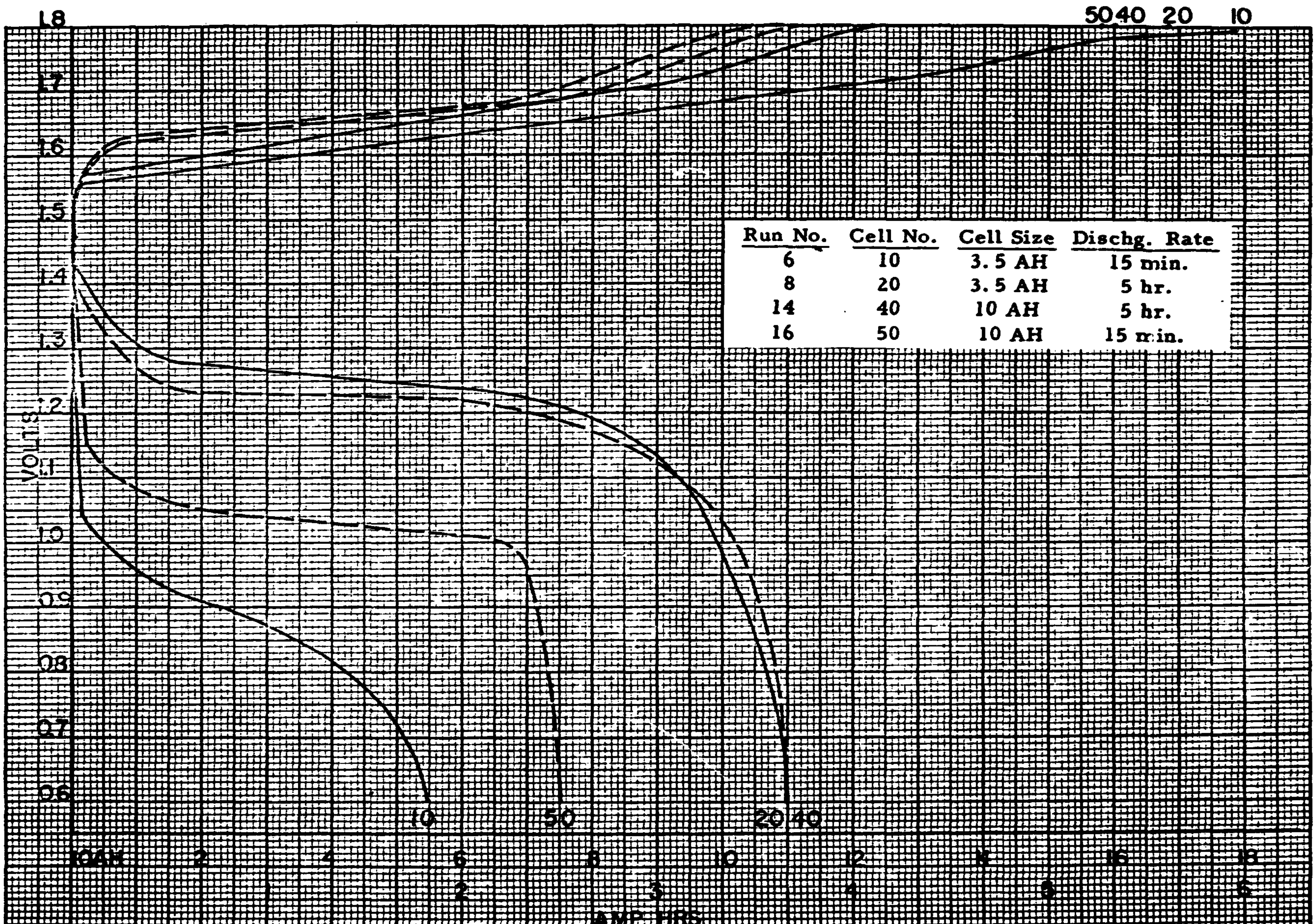


Figure 30 Charge and Discharge Characteristics at -10°F

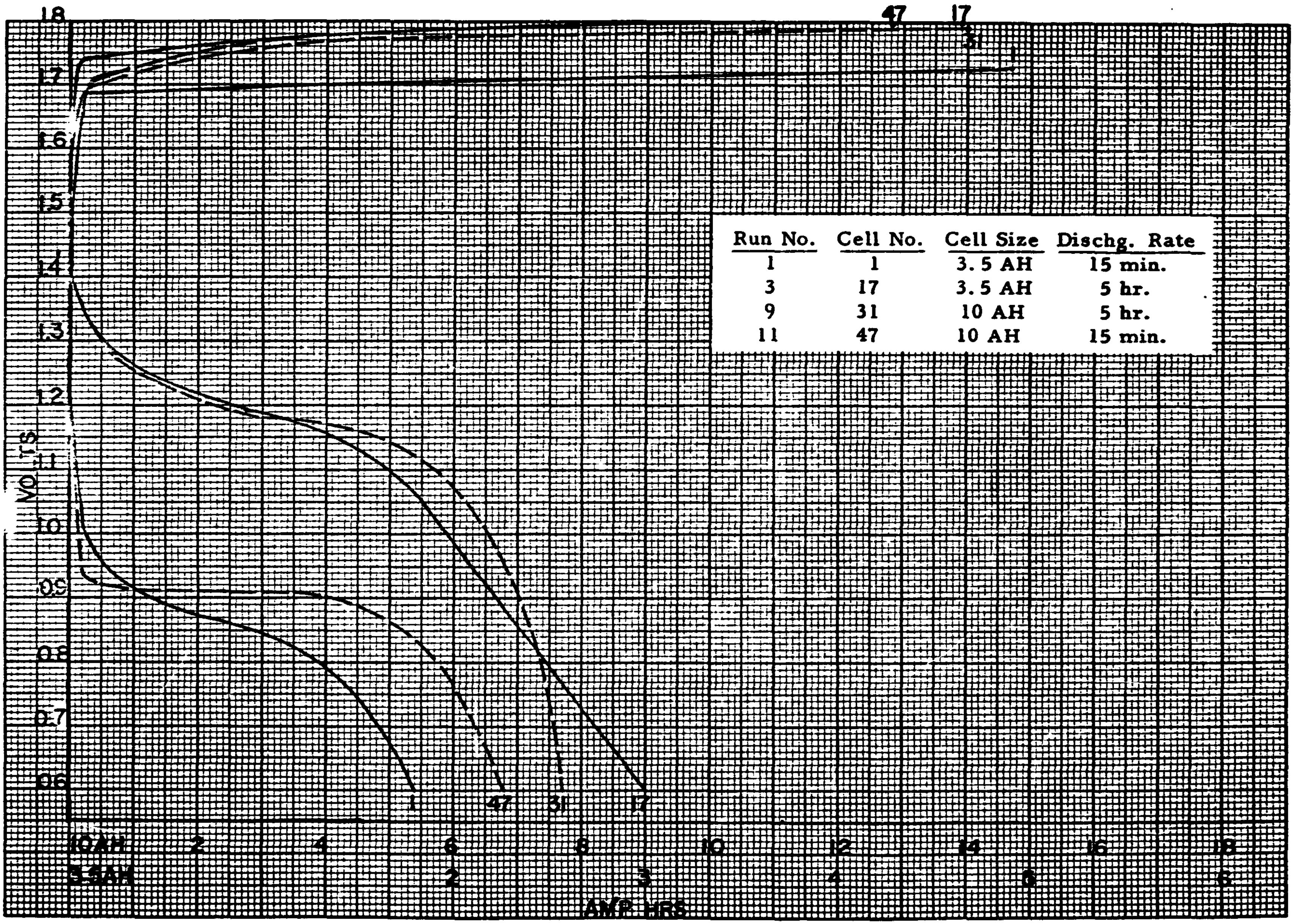


Figure 31 Charge and Discharge Characteristics at -40°F

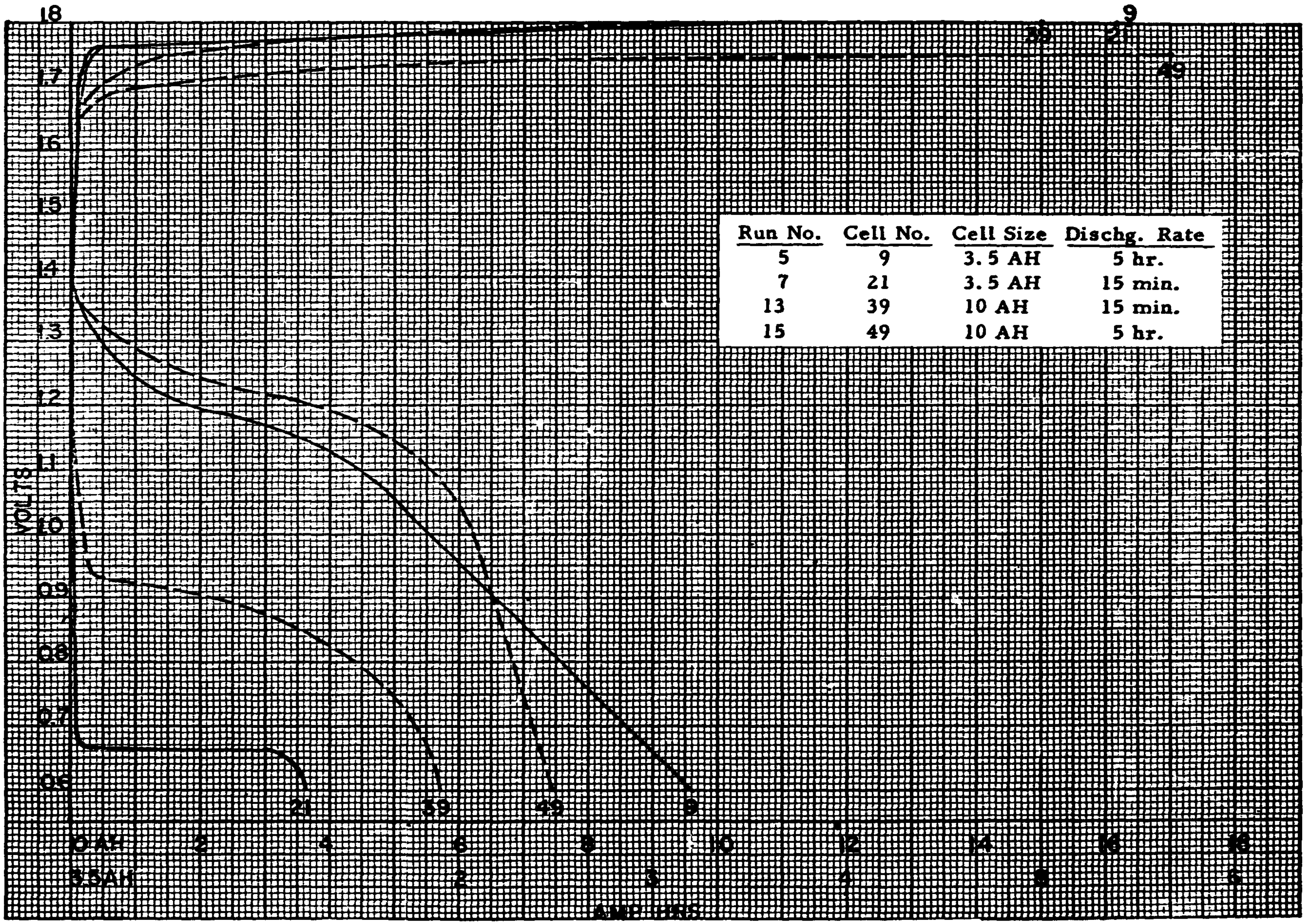


Figure 32 Charge and Discharge Characteristics at -40°F

D. Test Instruments

Ambient temperatures for the tests described in this report were maintained within ± 2°F. Following is a list of the major types instruments and equipment used to perform the tests:

Item	Mfr.	Model or Type No.
Power Supplies	Harrison Labs.	814A
Power Supplies	Harrison Labs.	855B
Power Supplies	Electro Prod. Lab.	NFA
Recorder, 2-Channel	Offner Electronics	Dynograph, Type P
Recorder (V & I)	M-H	153X60P6-X-1
Recorder (Temp.)	M-H	153X60P16-X-31
Voltmeter, D. C.	Weston	931, 5000 ohms/v.
Voltmeter, D. C.	Sensitive Research	University, 5000 ohms/v.
Ammeter, D. C.	G. E.	8DP9ACU1
Milliameter, D. C.	Weston	741
Milliameter, D. C.	Sensitive Research	UPP
Timer	G. E.	Telechron - 12"

V. CONCLUSIONS

Since only a portion of one charging method (constant-current) has been investigated in this program at the present time, no conclusions can be drawn with regard to the optimum charging method(s) for sealed nickel-cadmium cells. However, analysis of the data obtained in Experiments I and II reveal the following:

1. In each of the two experiments conducted with constant current charging procedures for fully discharged cells, ambient temperature and discharge rate, for the ranges selected for these variables, were the main factors controlling the capacity which could be obtained from the cells. (The average capacity output of the cells to 1.0 volt was considerably greater at 75°F than at the temperature of 125°F, and the average capacity output to 0.6 volt was considerably higher at -10°F than at -40°F. The average capacity output of the cells for all charges conducted was considerably greater at the five-hour discharge rate than at the fifteen-minute rate.)
2. In each experiment, the performance of the larger cells (10 A-H) was better than the smaller cells (3.5 A-H) at the fifteen-minute discharge rate. (This is attributed to the difference in the cell designs.)
3. Percent overcharge was not a controlling factor in either experiment at the ranges selected for this variable.

From the results obtained, it is believed, the experiments indicate which variables and ranges could be investigated further and that the experiments will aid in determining the significant variables in the other charging methods to be studied.

VI. PROGRAM FOR THE NEXT INTERVAL

Investigation of constant current charging procedures with cells initially at 33 and 66% states of charge at 75°F and investigations into the constant potential charging procedurs are planned for the next quarterly report period.

VII. IDENTIFICATION OF KEY TECHNICAL PERSONNEL

Key technical personnel of the contractor contributing to the technical effort and supervision of the work of the program covered by this report and the approximate man-hours of work performed by each are listed below:

Name	Title	Approximate Man-Hours
W. G. Ingling	Mgr., ITL Dayton Labs.	30
I. F. Luke	Project Engineer	80
R. L. Koesters	Engineer	220
J. L. McGee	Sr. Reliability Engineer	16
D. R. Belle	Technician	205
R. E. Cobb	Technician	100

Following is a brief description of the background of each person listed above:

W. G. Ingling

Mr. Ingling has been actively engaged in engineering and technical management since 1940. His responsibilities have included supervision and control of facilities and technical personnel engaged in environmental testing, product evaluation, failure analysis, specification engineering, and product improvement. Projects in these areas have included electronic and electromechanical components, quartz crystals, flight instruments and

controls, coaxial switches, automated test equipment, communications equipment, power conversion devices and batteries. During the last three years, the greatest portion of his efforts have been expended on projects involving evaluation and analysis of sealed alkaline batteries. Mr. Ingling was project engineer on programs for evaluation of quartz crystals, standardization and up-dating of military specifications, and radio interference control studies. His experience has also included considerable engineering liaison work with Government agencies and contractors. During the period of his military service, Mr. Ingling was Commanding Officer of a radar supply depot and Executive Officer of a Signal Depot with the rank of Captain in the U. S. Army. Mr. Ingling attended Sinclair College and received a degree in Electrical Engineering from the University of Dayton. He is author and co-author of published reports on coaxial switches and batteries and has presented technical papers covering secondary battery evaluations.

I. F. Luke

For the past 20 years, Mr. Luke has been engaged in engineering, equipment evaluation, analysis and testing services while associated with a Government agency and Inland Testing Laboratories. His experience and responsibilities have consisted of

technical supervision, direction and performance for programs in areas which include interpretation and analysis of test requirements and objectives, formulation of detail test procedures and specifications, design of special test instrumentation and fixtures, development of testing techniques and statistical experiments, equipment failure analysis and engineering modifications, data reduction and analysis and preparation of technical reports. In recent years the majority of Mr. Luke's efforts expended in these areas have pertained to projects involving sealed batteries designed for space applications. Other projects have involved electronic, electro-mechanical, hydraulic and pneumatic components and assemblies including tubes, capacitors, resistors, relays, switches, valves, servos, power supplies, flight instruments, transmitters, receivers, cables, connectors, test sets and similar items. Mr. Luke has a Bachelor of Science degree in Electrical Engineering from Purdue University and has been co-author of published technical reports and papers on batteries and relays.

R. L. Koesters

Mr. Koesters has been actively engaged in engineering for the past 4 years and was graduated from the University of Dayton with a Bachelor degree in Electrical Engineering. As an engineer on the staff of Inland Testing Laboratories he has been engaged

engaged in the design of test circuits and fixtures, preparation of test procedures and technical reports, and performance and supervision of evaluation and environmental test programs. Items included in these programs were power conversion units, batteries, temperature instruments, synchros, timers, pumps, gauges, tachometer generators, gyros and field test sets. While attending the University of Dayton, Mr. Koesters was employed as a Technician at Inland Testing Laboratories and performed various types of laboratory tests. Prior to this association, he was employed as an electrician to service and repair electric motors and controls.

J. L. McGee

Mr. McGee has had eight years experience in the planning and preparation of test programs requiring verification of specific reliability requirements in accordance with military and/or industry requirements. In addition, he has been responsible for training personnel in reliability procedures and test methods, including paper prediction studies, design reviews, statistical analysis of product performance from test data, and sequential testing procedures. Mr. McGee holds a B.S. Degree with Physics-Math Major from Murray State College and has had graduate courses in Statistical Analysis.

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D. R. Belle

Mr. Belle is a senior student in the School of Electrical Engineering co-operative program with the University of Detroit and has been associated with Inland Testing Laboratories on a co-operative work basis since Nov. 1960. During the last 1 1/2 years, he has been performing tests such as capacity, overcharge, electrical and electrolyte leakage, internal resistance, life-cycling and environmental tests on sealed batteries. Performance of these tests included the functions of data recording, instrumentation and test circuitry, and test fixture and equipment assembly. Prior to this testing experience, Mr. Belle conducted operational and environmental tests on communications equipment, and assembled and tested battery charging equipment.

R. E. Cobb

Mr. Cobb is also a senior student in the School of Electrical Engineering co-operative program with the University of Detroit and has been associated with Inland Testing Laboratories on a co-operative work basis since Aug. 1960. Mr. Cobb's experience and work assignments have been very similar to those described above for Mr. Belle. The work periods of Mr. Cobb and Mr. Belle have been alternated with an "overlapping" period of one week. These "overlapping" periods permitted coordination of

detail test techniques and methods and continuity of work effort between the technicians.

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Cook Electric Company
Inland Testing Laboratories, Dayton, Ohio
INVESTIGATIONS LEADING TO THE DEVELOPMENT OF THE OPTIMUM METHOD(S) FOR CHARGING SEALED NICKEL-CADMIUM BATTERIES
by I. F. Luke, R. L. Koesters
Quarterly Progress Report No. 1, 1 October 1962 to 31 December 1961, 72 pp incl. illus., tables
Cont. DA 36-039-SC-90823, Unclassified Report

Experiment designs, test data, analyses and results for investigation of constant current charging at 75°F, 125°F, -10°F, and -40°F for fully discharged cells of Types BB412 and BB440 are presented. Since only one method has been investigated, no conclusions are drawn pertaining to charging methods, but analysis of the data shows that temperature, discharge rate, and cell type are the main factors controlling capacity obtained over the selected levels of the test variables.

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1. Nickel-Cadmium Battery

I. USAELRDL

II. Contract DA-36-039 SC-90823

III. DA Proj. No. 3A99-09-002

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